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COMPARISON OF MEYER AND MORTON EVAPORATION TECHNIQUES FROM OPEN WATER SURFACES

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ABSTRACT

The consistency between the Meyer and Morton techniques for estimating both pan-size an lake-size open water evaporation were tested, using the climatological data from 11 stations on the Canadian Prairies and 9 stations in Shaanxi, China. An attempt was made to evaluate these methods, using evaporation pan data from the above stations as control data, and interpolated values of evaporation obtained from the Mean Annual Lake Evaporation map provided by Fisheries and Environment Canada (1978). The results of this study showed that the Meyer model consistently over-estimates open water evaporation for both pan-size and lake-size water bodies, while the Morton model produces under-estimated pan-size evaporation. In the case of Morton pan-size evaporation, this result does not agree with Morton's definition that pan-size evaporation is equivalent to the evaporation from the U.S. Class A pan or potential evaporation. The Meyer computations consistently exhibit slightly higher correlations with pan data than the Morton methods does.

For estimating lake-size evaporation, neither the Meyer nor the Morton methods demonstrate any significant advantage over the other in our analyses, possibly because no control lake evaporation data set was available for this study. An attempt to use interpolated lake evaporation data from a published mean annual lake evaporation map did not yield sufficient accuracy for a comparative evaluation of the Meyer and Morton methods. The analyses presented here indicate that the uncertainty in a single monthly value of open water evaporation may be as high as ±50% for either Meyer or Morton estimates.

It is recommended that, for a detailed evaluation of the Meyer and Morton lake-size evaporation techniques, and determination of the best choice of the two methods, careful water budget studies need to be carried out, using artificially-lined reservoirs of varying sizes and exposures. Such a project would also help to fine-tune existing operational methods, and provide the means to develop improved techniques for estimating open water evaporation. In the meantime, it is demonstrated here that a simple average of comparable Meyer and Morton computations is apt to yield more accurate results for some operational needs than either method alone.

RÉSUMÉ

L'uniformité des résultats obtenus par les méthodes de Meyer et de Morton pour l'estimation de l'évaporation depuis des étendues d'eau libre des dimensions d'un bac évaporométrique et de celles d'un lac a été éprouvée à l'aide de données climatologiques provenant de 11 stations des Prairies canadiennes et de 9 stations du Shaanxi en Chine. Une évaluation de ces méthodes a été tentée avec les données sur l'évaporation depuis des bacs aux stations déjà mentionnées utilisées comme donnés de contrôle et des valeurs interpolées de l'évaporation tirées de la Carte de l'évaporation annuelle moyenne depuis les lacs fournie par Pêches et Environnement Canada (1978). Les résultats de cette étude montrent que le modèle de Meyer surestime de manière uniforme l'évaporation depuis les étendues d'eau libre des dimensions d'un bac et de celles d'un lac, alors que le modèle de Morton sous-estime l'évaporation dans le cas des bacs. Dans le cas de l'évaporation depuis des bacs par la méthode de Morton, ce résultat ne correspond pas avec la définition de Morton voulant que l'évaporation depuis des bacs soit équivalente à l'évaporation depuis le bac évaporométrique américain de classe A ou à l'évaporation potentielle. Les calculs de Meyer indiquent uniformément des corrélations légerement plus élevées avec les données obtenues avec des bacs évaporométriques que la méthode de Morton.

Pour l'évaporation depuis des lacs, la méthode de Meyer et celle de Morton ne présentent aucun avantage important l'une par rapport à l'autre d'après nos analyses, peut-être parce qu'aucun ensemble de données de contrôle sur l'évaporation depuis des lacs n'était disponible pour la présente étude. La tentative d'utilisation de données interpolées sur l'évaporation depuis des lacs tirées d'une carte publiée de l'évaporation annuelle moyenne depuis des lacs n'a pas permis une précision suffisante pour permettre une évaluation comparée des méthodes de Morton et de Meyer. Les analyses ici présentées indiquent que l'incertitude rattachée à une unique valeur mensuelle de l'évaporation depuis des eaux libres peut atteindre ±50 %, tant pour les estimations de Meyer que pour celles de Morton.

Pour une évaluation détaillée des méthodes de Meyer et de Morton de calcul de l'évaporation depuis un lac permettant de déterminer la meilleure des deux, il est recommandé que soient effectuées des études minutieuses de bilans hydriques pour des réservoirs avec revêtement artificiel de différentes dimensions et différemment exposés. Un tel project aiderait également à

raffiner le méthodes opérationnelles existantes et permettrait de mettre au point des méthodes améliorées d'estimation de l'évaporation depuis des étendues d'eau libre. Entre temps, il est ici démontré qu'une simple moyenne des résultats obtenus par les méthodes de Meyer et de Morton fournirait, pour certains besoins opérationnels, des résultats plus précis que ceux obtenus par l'une ou l'autre méthode prise séparément.

PREFACE

Accurate estimates of evaporation from lakes, reservoirs and other open water bodies is important for practical applications and scientific studies in hydrology, water resources development and management, and many related fields on the semiarid Canadian Prairies. The Prairie Provinces Water Board (PPWB) Committee on Hydrology (COH) has expressed concerns over present methods of estimating evaporation, and the need for comparative evaluations, most specifically between the Morton method, favored in Alberta for water apportionment, and the Meyer formula, which is preferred in Saskatchewan and Manitoba. A draft document, "*Guidelines for Evaporation Estimates Required by the Prairie Provinces Water Board*" (Appendix I of Strong, 1989), was prepared for the PPWB by the COH. This document requests that the National Hydrology Research Centre (NHRC) assume a lead role in a study of evaporation on the Prairies.

The NHRC, represented by the Hydrometeorological Research Division of AES and the National Hydrology Research Institute, responded to these concerns and commenced the **Prairie Evaporation Study (PES)** in April, 1988. One of the objectives of the **Prairie Evaporation Study (PES)** is to "*use existing data sets to determine the consistency of results between various techniques used to estimate open-water evaporation; in particular, intercompare the Meyer and Morton methods, as well as evaporation pan estimates*" (Strong, 1989). For this purpose, several studies intercomparing these and other methods have been commenced.

This report represents the first of these studies. It briefly describes the two techniques, the Morton and the Meyer open water evaporation models, and presents the preliminary results of the intercomparison study. It is anticipated that these results highlight the major weakness in current operational techniques, and present a number of conclusions and recommendations which will prove very useful in both scientific and technical planning of the Prairie Evaporation Study.

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ABSTRACT

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For estimating *lake-size* evaporation, neither the Meyer nor the Morton methods demonstrate any significant advantage over the other in our analyses, possibly because no control lake evaporation data set was available for this study. An attempt to use interpolated lake evaporation data from a published mean annual lake evaporation map did not yield sufficient accuracy for a comparative evaluation of the Meyer and Morton methods. The analyses presented here indicate that the uncertainty in a

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It is recommended that, for a detailed evaluation of the Meyer and Morton *lake-size* evaporation techniques, and determination of the best choice of the two methods, careful water budget studies need to be carried out, using artificially-lined reservoirs of varying sizes and exposures. Such a project would also help to fine-tune existing operational methods, and provide the means to develop improved techniques for estimating open water evaporation. In the meantime, it is demonstrated here that a simple average of comparable Meyer and Morton computations is apt to yield more accurate results for some operational needs than either method alone.

1. INTRODUCTION

Evaporation, as one of the main phases of hydrological cycle on the earth, withdraws about sixty-one percent of the continental annual precipitation into the atmosphere (Korzun et al., 1978). Evaporation loss from open water surfaces, such as lakes, reservoirs and other open water bodies, is often several times higher than precipitation in arid and semiarid areas in the world, and constitutes a major component of the water balance of these open water bodies. As such, open water surface evaporation processes impact considerably on water resource management, water engineering and apportionment, environmental and climate change studies, and the planning and design for wildlife habitats, hydro-electric power, and reservoir engineering. In other words, evaporation processes from open water surfaces play an important role in the hydrologic cycle; water resources evaluation, and all related studies.

The actual physical process of evaporation has been well understood since at least the time of Dalton (1802). Perhaps for this reason, it has received less attention from scientists than other atmospheric processes. The real problem is more one of technology, in that evaporation cannot be measured directly, much less accurately, as can temperature, air pressure, or other such variables. Nevertheless, assessing the magnitude and variability of open water evaporation is an important aspect of the information needed for water resources development and management, water engineering planning design and operation, and water apportionment and

supply. Therefore, accurate calculations of open water evaporation are important for both practical applications and scientific studies.

In order to conduct scientific research on open water evaporation processes and their effects on the environment and general ecosystem, many estimation techniques have been developed. Some examples are Meyer (1915, 1942), Penman (1948), Kohler et al. (1955), Kuzmin (1957), Christiansen (1966, 1968), Kohler and Parmele (1967), Priestley and Taylor (1972), Brutsaert and Stricker (1979), Morton (1983a, 1983b, 1986), and Mawdsley and Ali (1985). Some of these methods have been in practical use in specific areas, including the Meyer formulation (Meyer 1915, 1942), while others have seen general application worldwide, such as the Penman formulation (Penman, 1948) and the formulation of Kohler et al. (1955).

These methods or techniques for estimating evaporation from open water surfaces can be classified into three groups (Winter, 1981; Kuusisto, 1985), i.e., (1) balance methods, including energy balance and water balance; (2) comparative methods, such as direct measurements from evaporation pans, modified by the evaporation pan coefficients; and (3) aerodynamic methods, including the eddy correlation, mass transfer and gradient methods. Almost all of the existing methods or techniques, whether theoretical or empirical, and combinative or individual, originated from these three groups of methods, and were developed under certain geographic and climatic conditions. Some of the methods require only simple routing of climatological data and are easy to use, such as

the Linacre formulation (Linacre, 1977), which requires only temperatures from climatological observations. Some other methods are quite complicated, and need special data which are often not available, together with locally-modified empirical coefficients.

For practical applications, operational methods are expected to produce reasonable accuracy, be easy to manipulate, and use readily available data. As a result, there will be some inevitable limitations for the practical application of most of the existing methods to different areas, varying climatic conditions, and the use of databases without locally-optimized empirical coefficients. In other words, it may not be possible to apply some of the methods to conditions which are different from those in which the methods originated. Because of these limitations, it becomes necessary to choose a "*best*" approach from the existing methods for special use. Nevertheless, to make the "*best*" choice is often difficult, and has to be based on a careful comparison of the alternative methods with one or more "*standard*" methods.

For the "*best*" choice, numerous comparisons have been performed. A typical example is the evaporation study on the Weyburn Reservoir, in Saskatchewan, Canada, carried out by McKay and Stichling (McKay and Stichling, 1961, McKay, 1962). In their study, eight methods, including the Class A evaporation pan, Meyer (1942), and Penman (1948), were used to estimate the reservoir evaporation, employing data obtained from the reservoir and surrounding area. Coleman and DeCoursey (1976) analyzed the

variable sensitivity and error variance of six evaporation and evapotranspiration models, of which five models were applied to open water surface evaporation. Recently, Warnaka and Pochop (1988) performed a statistical comparison and analysis of six methods for estimating open water evaporation, including Penman (1948), Kohler et al. (1955), and Priestley and Taylor (1972), using climatological data. Andersen and Jobson (1982, 1983) compared annual lake evaporation estimates from the Morton CRLE model (Morton, 1979) with those from the evaporation map of the U.S. Weather Service (Kohler et al, 1959), and reported evaporation values for 28 lakes in the United States. Sharma (1988) compared lake evaporation estimates from the Morton model (Morton, 1983a) with those from the Penman formulation (Penman, 1948) in the Zambian environment. Major difficulties in comparing results from such studies arise from the fact that the various formulations are based on a number of different physical bases, and that the measurement "*standards*" for water balance data vary greatly.

The Meyer and Morton open water evaporation techniques are generally accepted to be suitable for the Canadian Prairies, one of the semiarid regions of the world. The Meyer approach, reported to provide reasonable evaporation estimates with its simple formulation (Mckay, 1962; Ferguson et al., 1970), has been used operationally on the Prairies for more than 30 years, but with continuous rationalization of formulations used for data adjustment and transfer (PPWB, 1952; Berry and Stichling, 1954; Buckler and Quine, 1971; Buckler, 1973; Wiens, 1978; Martin, 1988). The

Morton technique, which requires only land environment observations of temperature, humidity and sunshine duration as inputs, also provides reasonable evaporation estimates, is easy to use, and is purported to be appropriate to worldwide application without locally-optimized coefficients (Morton, 1983a, 1983b, 1986; Morton et al., 1985). Even so, it is uncertain which of these two methods, Meyer's or Morton's, is most appropriate, and under what constraints, for the Canadian Prairies or other areas with similar environmental and climatic conditions to the Prairies, such as the arid and semiarid areas of China.

Therefore, the purpose of this study is to intercompare the results of evaporation estimates from the Meyer and Morton open water evaporation techniques, and at least one other estimation technique, and to evaluate the degree of consistency between them. The third technique chosen was the U.S. Class A evaporation pan, since the stations which provide the climatological data necessary for Meyer and Morton computations, in general, also provide pan data. Lake evaporation data interpolated from the Mean Annual Lake Evaporation map provided by Fisheries and Environment Canada (1978) were used for comparisons of lake evaporation estimates from the Meyer and Morton methods. The intercomparison of these methods focussed on estimates of *pan-size* and *lake-size* (or shallow-lake) evaporation.

2. METHODS AND DATA

The derivation of the Meyer and Morton open water evaporation methods, classified as empirical or semi-empirical methods, are presented in what follows. The data used in this study are then briefly described.

2.1 Meyer Method

The Meyer formulation is one of many forms of the mass transfer (or bulk aerodynamic) method derived from Dalton's open water surface evaporation theory developed in the early 1800s (e.g., see Gray, 1970; Eagleson, 1970; Winter, 1981; Brutsaert, 1982; Kuusisto, 1985). Based on Dalton's evaporation theory, Meyer developed his empirical formulation in the early 1900s, and later provided small modifications to the technique (Meyer, 1915, 1942). The Meyer formulation for open water surface evaporation is given as follows:

$$E = C\ (1 + 0.1\ u)(e_w - e_a) \qquad (1)$$

where E is monthly evaporation in inches; e_w is the saturation vapor pressure in inches of mercury, corresponding to the mean temperature of the surface water measured about one foot below the water surface; e_a is the actual vapor pressure in inches of mercury at 25 feet above the water surface; u is the wind speed in miles per hour measured at 25 feet above the water surface or corresponding height in the land environment; and C

is the Meyer coefficient (or evaporation coefficient), and depends on the time of vapor pressure, temperature, and humidity observations, and the size and character of the water body.

The original values for the evaporation coefficient recommended by Meyer (1942) are: 15 for monthly evaporation from fully exposed pans, small puddles, and wet soil and vegetation surfaces when moisture is not limited; 11 for monthly evaporation from small lakes and reservoirs when the actual vapor pressure is determined from the mean of the maximum and minimum temperatures and the mean of morning and evening relative humidity measured at 25 feet above the water surface or the ground; and 10 for monthly evaporation from small lakes and reservoirs when the actual vapor pressure is the mean of morning and evening values or of more frequent, equally spaced determinations of actual vapor pressure at 25 feet above the water surface or the ground. In the latter situation, a C-value of 10.1 was also recommended by Meyer (1942) in his analysis on the coefficient.

Recently, Martin (1988) suggested that, for small lakes and reservoirs, the C-value be 10.1 when dew point data from four daily observations are used to determine actual vapor pressure, and 11.0 when the dew point data are based on two daily observations. For large, deep lakes and reservoirs on the Prairies such as Lake diefenbaker, a C-value of 9.0 was suggested (Martin, 1988). Adopting Martin's (1988) above recommendation for lake evaporation for this study, a C-value of 10.1 was

used for estimating small and "shallow" lake evaporation, and a C-value of 13.8 was used for *pan-size* evaporation on the Canadian Prairies. The C-value of 13.8 was obtained from the product of the ratio of 10.1 (Martin, 1988) to 11.0 (Meyer, 1942) and the original *pan-size* evaporation coefficient 15.0 (Meyer, 1942) due to the change in the database of actual vapor pressure.

According to Meyer's (1942) description, Equation 1 was re-defined (PPWB, 1952; Berry and Stichling, 1954; Buckler and Quine, 1971; Buckler, 1973; Martin, 1987, 1988) as follows:

$$E = C\ (1 + 0.1\ u)(e_w - e_a)(1 + 10^{-5}\ H) \qquad (2)$$

where H is the elevation above sea level of the water surface in feet; and all other symbols are as defined in Equation 1. To convert Equation 2 in metric units it becomes

$$E = 0.75\ C\ (1 + 0.062\ u)(e_w - e_a)(1 + 3.28\times10^{-5}\ H) \qquad (2a)$$

where the evaporation, E, is in mm; the vapor pressures, e_w and e_a, are in mbar; the wind speed, u, is in km hr^{-1}, and the elevation, H, is in m.

Equation 2a was used in the comparison with the following equations for adjustment and modification of surface water temperature (T_w), actual vapor pressure (e_a) and wind speed (u).

For the monthly mean surface water temperature, T_W in °C,

$$T_W = B + 0.60\ T_A \qquad (3)$$

where T_A is monthly mean air temperature in °C, based on the average of the daily mean temperature calculated from daily maximum and minimum temperatures; and B is a constant depending on the months under consideration. The constant B has the following values by month (Martin, 1988):

January	-3.0	February	-2.8	March	-1.4	April	2.0
May	7.3	June	8.8	July	10.0	August	9.6
September	7.1	October	3.0	November	-1.2	December	-6.6

For the monthly mean vapor pressure e_a in mbar, at 7.6 m (25 ft) above ground level,

$$e_a = (0.8559 + 0.094 \log e_{apm})e_{ap} \qquad (4)$$

where e_{ap} is the preliminary monthly mean vapor pressure in mbar, derived from climatological observations at the official observing level of 1.22 m; and e_{apm} is the mean of the April to October climatological average values of e_{ap} for the calendar year in mbar. Both Equations 3 and 4 were derived by Martin (1988).

For the wind speed u in km hr^{-1}, at 7.6 m (25 ft) above ground,

$$u = u_r(7.62/z_r)^{0.25} \quad (5)$$

where u_r is the wind speed measured at the z_r-meter level above ground in km hr^{-1}; and z_r is the measuring height of the wind speed, and is equal to 10 m in the present study; that is, $u = 0.9343\ u_{10}$. The exponent 0.25 in Equation 5 was recommended by Buckler (1969), and has since been applied on the Prairies (Buckler and Quine, 1971; Buckler, 1973; Wiens, 1978; Martin, 1988).

For the computation of vapor pressure, the Richards (1971) formulation was used in this study because its accuracy is within ±0.01 percent of the commonly accepted Goff-Gratch formulation (e.g., List, 1984) in the range of temperature from -50 °C to 140 °C. Richards (1971) formulation for saturation vapor pressure, e^*, in mbar, is as follows:

$$e^* = p_s \exp(13.3185\ T_r - 1.9760\ T_r^2 - 0.6445\ T_r^3 - 0.1299\ T_r^4) \quad (6)$$

where p_s = 1013.25 mbar; and $T_r = 1-(373.15/T)$ in which T is absolute temperature in K. When Equation 6 is used to calculate the saturation vapor pressure at the water surface (e_w), T becomes the surface water temperature (T_w) as in Equation 3 in K. For the actual vapor pressure in the air (e_a), T is replaced by the dew point temperature in K (Martin, 1988).

2.2 Morton Model

The Morton technique for estimating *pan-size* and *lake-size* (or shallow-lake) evaporation is referred to as the complementary relationship wet-surface evaporation (CRWE) model. The CRWE model is the extension of the complementary relationship areal evapotranspiration (CRAE) model, which is based on Bouchet's (1963) concept of complementary relationship between potential evapotranspiration and areal evapotranspiration (Morton, 1978, 1979; Morton et al., 1980; Morton, 1983a, 1983b, 1986; Morton et al., 1985). The original complementary relationship (Bouchet, 1963) can be expressed as follows:

$$ET_A + ET_P = 2ET_{WA} \tag{7}$$

where ET_A is areal evapotranspiration in mm; ET_P is potential evapotranspiration in mm; and ET_{WA} is the wet-environment areal evapotranspiration in mm.

In Morton's most recent version of the CRAE model (Morton, 1983a; Morton et al., 1985), the following equations are used in order to estimate the potential evapotranspiration (ET_P) and the wet-environment areal evapotranspiration (ET_{WA}).

$$ET_P = R_T - \lambda f_T (T_P - T) \tag{8}$$

$$R_{TP} = ET_P + \gamma p f_T (T_P - T) \quad (9)$$

$$ET_{WA} = b_1 + b_2 (1 + \gamma p/\Delta_P)^{-1} R_{TP} \quad (10)$$

and

$$1/2\ ET_P \leq ET_{WA} \leq ET_P \quad (11)$$

where R_T is the net radiation for soil-plant surfaces at air temperature (T) in evapotranspiration equivalent unit; R_{TP} is the net radiation for soil-plant surfaces at potential evapotranspiration equilibrium temperature (T_P) in evapotranspiration equivalent unit; λ is the heat transfer coefficient, with the value of $\lambda = \gamma p + 4\epsilon\sigma(T+273)^3/f_T$ in which ϵ is the surface emissivity (ϵ = 0.92 for land surface, and 0.97 for water surface) and σ is the Stefan-Boltzmann constant ($\sigma = 5.67\times10^{-8}$ W m^{-2} K^{-4}); f_T is the vapor transfer coefficient between the ground level and the instrument level, with the value of $f_T = (p_s/p)^{0.5} f_Z/\zeta)$ in which f_Z = 28.0 W m^{-2} mbar^{-1} when $T \geq 0$ °C and 28.0×1.15 W m^{-2} mbar^{-1} when $T < 0$ °C, and ζ is a stability factor; γ is the psychrometric constant ($\gamma = 6.5\times10^{-4}$ °C^{-1}, when the mean air temperature, $T \geq 0$ °C, or $6.5\times10^{-4}/1.15$ °C^{-1}, when $T < 0$ °C); p is the atmospheric pressure in mbar; Δ_P is the slope of the saturation vapor pressure curve at T_P; and b_1 and b_2 are constants. The constants b_1 and b_2 are 14 W m^{-2} and 1.20 for wet-environment areal evapotranspiration, and 13 W m^{-2} and 1.12 for lake evaporation, respectively.

The CRAE model was converted to the CRWE model by taking into account the modification of the air as it passes from the land environment to the environment of a shallow-lake; that is, pertinent parameters were appropriately modified, such as the albedo and emissivity from the land environment to the shallow-lake environment (Morton, 1979, 1983a). The CRWE model can provide evaporation estimates from *pan-size* and *lake-size* wet-surfaces, in which the *pan-size* wet-surface evaporation is equal to potential evaporation from the land environment or equivalent to U.S. Class A pan evaporation (Morton, 1983a, 1983b, 1986; Morton et al., 1985). According to Morton (1986), the complementary relationship wet-surface evaporation (CRWE) model can provide reliable estimates of annual evaporation from lakes and reservoirs with depths of up to 30 m by accumulating monthly estimates. The *pan-size* and shallow-lake evaporation therefore can be estimated by solving Equations 8 to 10 using the constraint given by Equation 11. In this case, ET_p and ET_{wl} represent the *pan-size* or potential evaporation (E_p) in the land environment and the *lake-size* or shallow-lake evaporation (E_L) respectively.

The CRWE model was further converted to the complementary relationship lake evaporation (CRLE) model (Morton, 1983a, 1983b, 1986; Morton et al., 1985), in order to estimate evaporation from deep lakes and reservoirs by taking into account the effects of depth, salinity, seasonal changes in sub-surface heat storage. To estimate evaporation from smaller ponds, the effects of the upwind boundary transition was taken into account.

2.3 Data

For the purpose of this study, 11 climatological stations on the Canadian Prairies were arbitrarily selected. Evaporation pans (U.S. Class A pan) were co-located with the instrumentation for the climatological observations at all but two of these stations. The exceptions were Lethbridge (3033880) and Medicine Hat, and for these, the pan evaporation data from the nearby sites, Lethbridge (3033890) and Manyberries, respectively, were applied. Fifteen years of data were used in the study, from January 1, 1972 to December 31, 1986. We shall occasionally refer to averages of these 15 years of data as "*long-term*" averages. Observing procedures were identical at all stations; for example, the wind speed data at all stations were 10-meter level observations. Table 1 provides the basic site information for these stations, as well as the annual average precipitation at each station, including Lethbridge (3033890) and Manyberries. The locations of these stations on the Prairies are shown in Figure 1. For the comparison of lake evaporation, mean annual lake evaporation values for the 11 Prairie stations were interpolated from the Mean Annual Lake Evaporation map provided by Fisheries and Environment Canada (1978). Also, as an additional cross-reference, some data from Shaanxi, China, were also used in the study. The Chinese data were used to demonstrate the transferability of the Meyer and Morton techniques and the consistency of their results to a climatological condition which is completely different from the condition that the methods were developed.

Table 1: Station information and annual precipitation for selected climatological stations on the Canadian Prairies.

Station Name	Station ID	Station Number	Elevation (m MSL)	Latitude (° ′)	Longitude (° ′)	PCPN[1] (mm)
Calgary	YYC	3031093	1084	51 06	114 01	351.6
Lethbridge	YQL	3033880	929	49 38	112 48	397.6
Lethbridge	YQL	3033890[2]	899	49 42	112 47	381.9
Medicine Hat	YXH	3034480	717	50 01	110 43	343.2
Manyberries	mb	3033200[3]	934	49 07	110 28	371.1
Broadview	WIK	4010879	601	50 23	102 35	388.9
Estevan	YEN	4012400	572	49 04	103 00	431.5
Regina	YQR	4016560	577	50 26	104 40	373.1
Saskatoon	YXE	4057120	501	52 10	106 41	351.6
Swift Current	YYN	4028040	817	50 17	107 41	366.0
Yorkton	YQV	4019080	498	51 16	102 28	445.6
Gimli	WGM	5013038	223	50 37	96 59	537.3
Winnipeg	YWG	5023222	239	49 54	97 14	395.7

[1] PCPN is the average annual precipitation during 1972-86.

[2] Lethbridge (3033890) pan evaporation data are used as those for Lethbridge (3033880).

[3] Manyberries pan evaporation data are used as those for Medicine Hat.

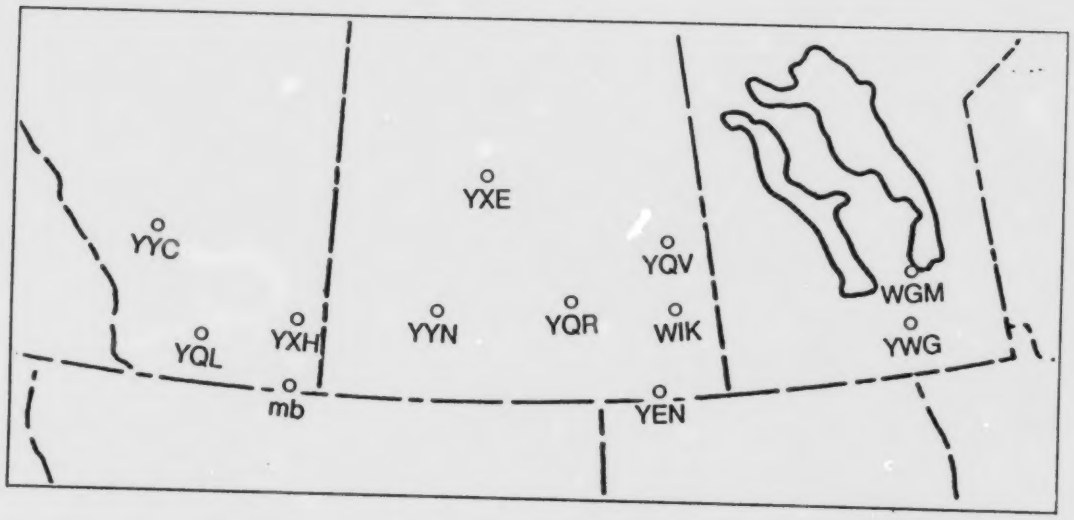


Figure 1: The locations of the climatological stations on the Canadian Prairies used in the open water evaporation study.

3. RESULTS AND ANALYSES

In this study, open water evaporation data from both *pan-size* and *lake-size* surfaces for the Meyer and Morton methods were simulated, using a 15-year climatological data sample for the 11 selected Prairie stations indicated in Table 1. The Meyer and Morton pan-size and lake-size evaporation estimates were then compared with evaporation pan observations from the same climatological stations, and lake evaporation data interpolated from the Mean Annual Lake Evaporation map provided by Fisheries and Environment Canada (1978) respectively. Calculations for the Morton pan-size evaporation were also carried out using a 10-year climatological data sample for nine stations in Shaanxi, China. Furthermore, evaporation pan observations and Meyer lake evaporation estimates from our simulations were compared with those carried out by McKay and Stichling (1961) and McKay (1962), who used field data from the Weyburn Reservoir in southeastern Saskatchewan, Canada.

Our results from the 11 Prairie stations indicated several consistent differences for open water evaporation estimates from both pan-size and lake-size surfaces between the Meyer model (Martin's 1988 version) and the Morton CRWE and CRLE models (Morton, 1983a; Morton et al., 1985). The results and main differences between the Meyer and Morton models, as well as the affecting factors, may be described as follows.

3.1 Results of Pan-size Intercomparisons

Pan-size evaporation using Martin's (1988) version of the Meyer model, with C = 13.8, and the Morton CRWE model (Morton, 1983; Morton et al., 1985) was calculated for the 11 selected Prairie stations listed in Table 1, excluding Lethbridge (3033890) and Manyberries which only provided pan evaporation data for Lethbridge (3033880) and Medicine Hat respectively. The pan-size evaporation estimates of June, July and August from both the Meyer and Morton models were compared with the evaporation pan observations of the corresponding months, which were available at the selected stations.

Figure 2 shows comparisons of long-term, three-month mean evaporation, June to August inclusive, between evaporation pan (U.S. Class A pan) observations and pan-size evaporation estimates from both the Meyer model (Figure 2a) and Morton model (Figure 2b) for each of the 11 selected stations; that is, the long-term averages of three-month total evaporation for each station are plotted in Figures 2a and 2b. On average, the relationship indicates that the Meyer pan-size evaporation estimates are higher than the evaporation pan observations, while the Morton pan-size evaporation estimates are lower than the evaporation pan observations.

For the pan data versus the Meyer and Morton estimates, the correlation coefficients of linear regression are 0.91 and 0.89 respectively (Table 2). Standard errors of the pan evaporation estimates

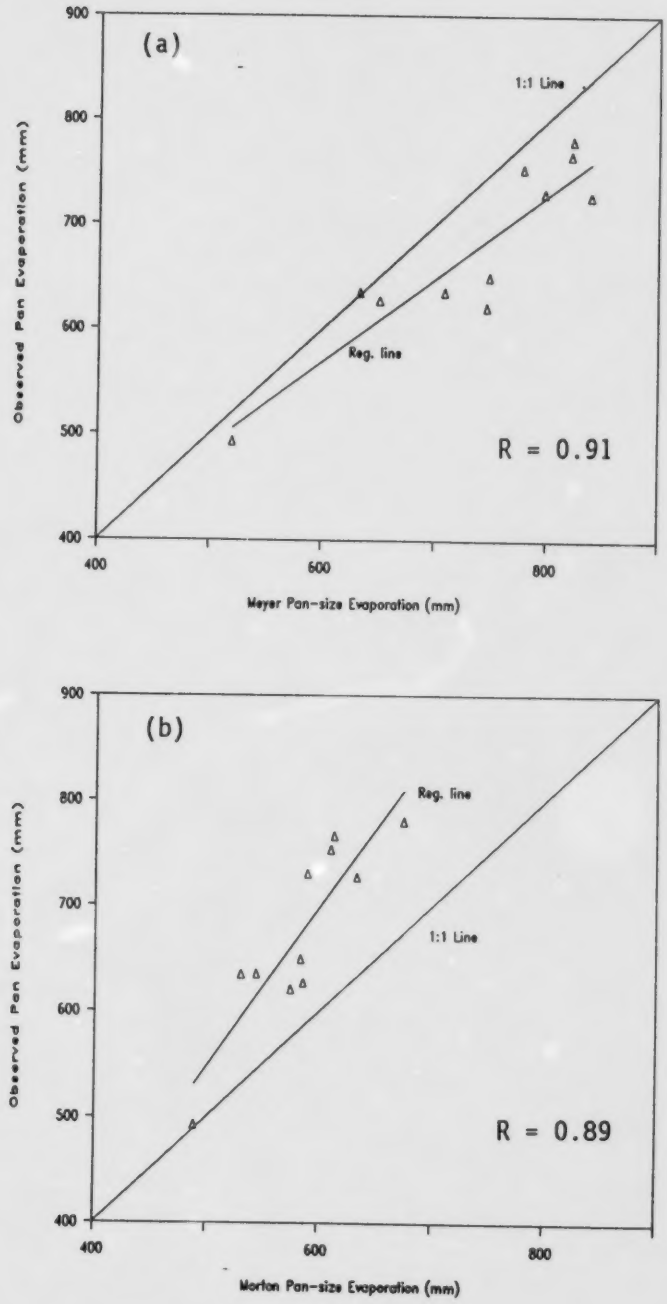


Figure 2: The relationship of long-term three-month averages between the evaporation pan observations and the pan-size evaporation estimates from (a) the Meyer model, and (b) the Morton model, from June to August, 1972-86, for each of the 11 stations on the Canadian Prairies.

Table 2: Linear regressions between evaporation pan observations and pan-size evaporation estimates of Meyer (C = 13.8) and Morton models, from June to August, 1972-86, at the 11 stations on the Canadian Prairies.

		Regression Coefficients a	b	Correlation Coefficient R	Standard Errors of Evaporation Pan Estimates
Long-term three-month average evaporation					
	Pan-Meyer[1]	91.09	0.80	0.91	37.23
	Pan-Morton[2]	-203.23	1.50	0.89	41.98
Annual three-month total evaporation					
	Pan-Meyer	98.51	0.79	0.85	56.44
	Pan-Morton	-158.39	1.43	0.83	59.84
Monthly evaporation					
June-August					
	Pan-Meyer	14.97	0.86	0.84	25.36
	Pan-Morton	-15.79	1.24	0.85	23.88
June	Pan-Meyer	34.87	0.80	0.83	21.29
	Pan-Morton	-16.75	1.25	0.80	22.73
July	Pan-Meyer	36.78	0.80	0.82	25.86
	Pan-Morton	-30.10	1.29	0.83	25.40
August	Pan-Meyer	-15.51	0.93	0.88	23.30
	Pan-Morton	-22.06	1.28	0.88	23.22

[1] Pan-Meyer represents linear regression $E_P = a + bE_{PMY}$, in which E_P is evaporation pan observations and E_{PMY} is Meyer pan-size evaporation estimates.

[2] Pan-Morton represents linear regression $E_P = a + bE_{PMT}$, in which E_P is evaporation pan observations and E_{PMT} is Morton pan-size evaporation estimates.

are 37.2 mm from the Meyer estimates and 42.0 mm from the Morton estimates respectively (Table 2). The comparisons of the Meyer and Morton estimates with the evaporation pan observations, presented in Table 3, indicate that the difference in long-term three-month averages from evaporation pans is +8.7% for the Meyer model, and -12.9% for the Morton model. These initial results suggest a high degree of consistency in evaporation estimates from station to station. However, we believe that this is also, in part, a reflection of consistent, high standards of data collection at these 11 sites. An interesting additional fact is that 63.6% of the Meyer estimates are within 10% of the pan observations, but only 27.3% of the Morton estimates fit this criterion. However, the reader is reminded that a different choice of the Meyer constant would raise or lower the 63.6% proportionally.

Figure 3 shows the relationship between annual three-month total pan evaporation observations for each year at each station, and the corresponding pan-size estimates from the Meyer model (Figure 3a) and the Morton model (Figure 3b). The relationship is similar to that shown in Figure 2, except the correlation coefficients are slightly lower (0.85, 0.83), and the standard errors are higher than those of the long-term, three-month mean evaporation estimates (Table 2).

Figure 4 breaks the relationship down further into individual monthly evaporation pan observations and estimates from the Meyer and Morton models for each of the three months, June, July and August, of each

Table 3: Comparisons of evaporation pan observations with pan-size evaporation estimates from the Meyer (C = 13.8) and Morton models, from June to August, 1972-86, at 11 Prairie stations on the Canadian Prairies.

Station name	Pan	Morton	Meyer	Morton-Pan		Meyer-Pan	
	E_P (mm)	E_{PMT} (mm)	E_{PMY} (mm)	ΔE_{PMT} (mm)	$\Delta E_{PMT}/E_P$ (%)	ΔE_{PMY} (mm)	$\Delta E_{PMY}/E_P$ (%)
Calgary	621.0	574.6	746.2	-46.4	-7.5	125.2	20.2
Lethbridge	727.5	632.5	839.3	-95.0	-13.1	111.8	15.4
Medicine Hat	780.5	673.7	822.6	-106.8	-13.7	42.1	5.4
Broadview	635.5	530.4	633.0	-105.1	-16.5	-2.5	-0.4
Estevan	753.6	609.5	778.5	-144.1	-19.1	24.9	3.3
Regina	730.2	589.1	797.6	-141.1	-19.3	67.4	9.2
Saskatoon	650.1	583.5	748.4	-66.6	-10.2	98.3	15.1
Swift Current	766.6	612.4	821.6	-154.2	-20.1	55.0	7.2
Yorkton	636.0	544.1	708.5	-91.9	-14.4	72.5	11.4
Gimli	492.9	488.6	520.4	-4.3	-0.9	27.5	.6
Winnipeg	627.4	585.7	650.5	-41.7	-6.6	23.1	3.7
Mean	674.7	584.0	733.3	-90.7	-12.9	58.7	8.7

Note: E_P = Evaporation pan observations.

E_{PMT} = Morton pan-size evaporation estimates.

E_{PMY} = Meyer pan-size evaporation estimates.

$\Delta E_{PMT} = E_{PMT} - E_P$.

$\Delta E_{PMY} = E_{PMY} - E_P$.

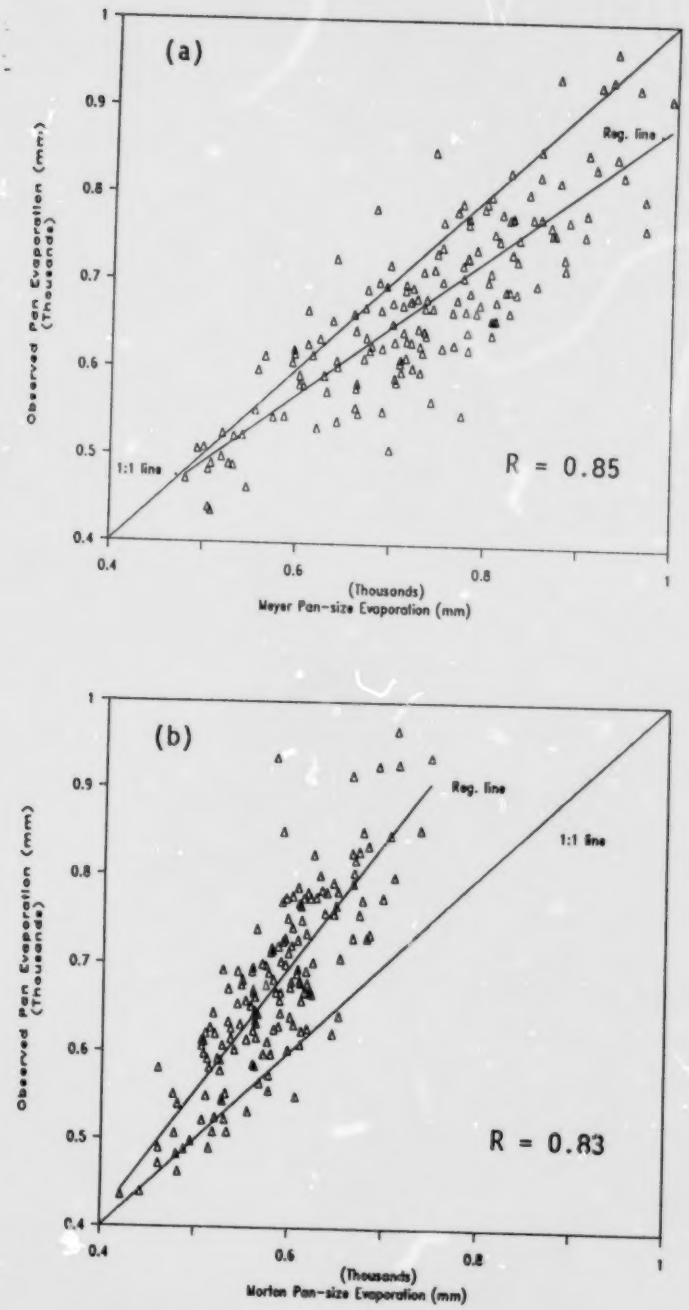


Figure 3: The relationship of annual three-month totals between the evaporation pan observations and the pan-size evaporation estimates from (a) the Meyer model, and (b) the Morton model, from June to August, for each year of 1972-86, at each of the 11 stations on the Canadian Prairies.

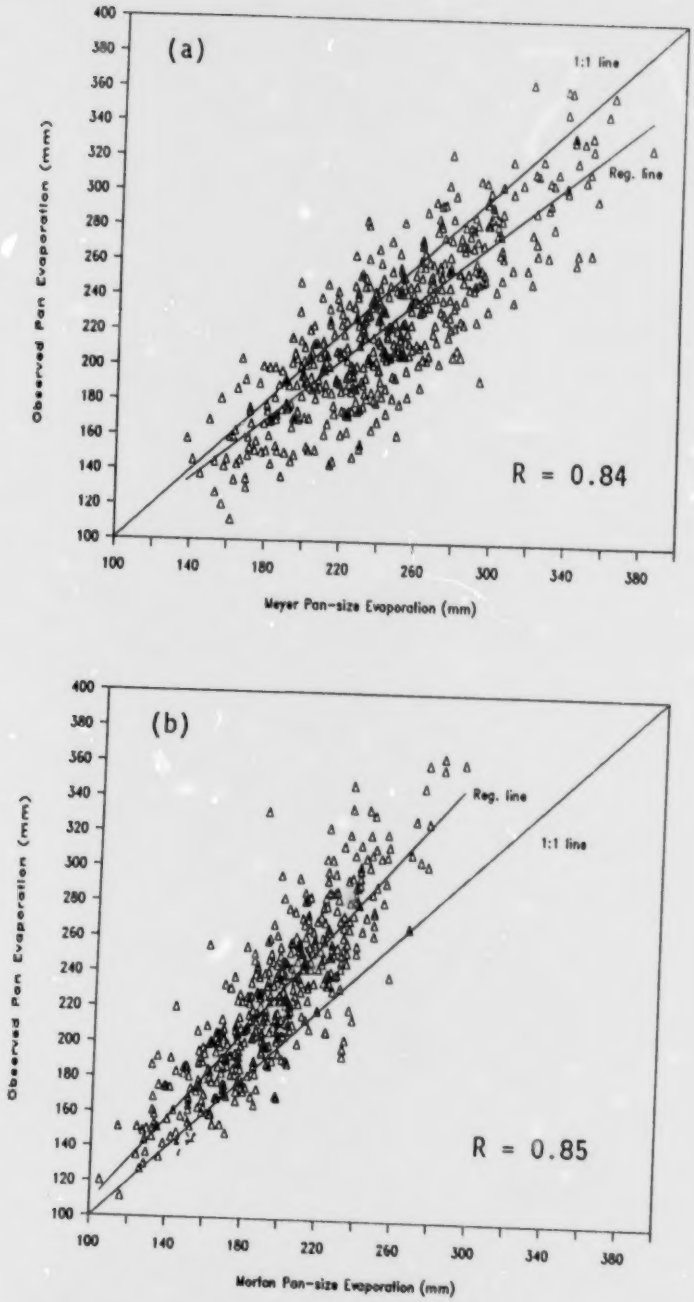


Figure 4: The relationship of monthly values between the evaporation pan observations and the pan-size evaporation estimates of (a) the Meyer model, and (b) the Morton model, for each of the three months, June, July and August, for each year of 1972-86, at each of the 11 stations on the Canadian Prairies.

year of 1972-86, and for each station, all plotted on one figure. Linear regression analyses for the monthly pan-size evaporation indicate that the correlation coefficient of evaporation pan observations versus the Meyer and Morton estimates are 0.84 and 0.85 respectively. The standard errors are 25.4 and 23.9 mm respectively (Table 2). Viewed in this gross way (Figure 4), there is little in the monthly mean values for individual stations to suggest that either method, Meyer or Morton, has any advantage over the other. This leads us to stratify the data by month.

The monthly relationships between evaporation pan observations and pan-size estimates of the Meyer and Morton models, June, July, and August inclusive, are given in Figures 5 through 7, respectively. The relationships are similar to those in Figures 2 to 4. Predictably, the correlation coefficients are quite similar, although fluctuations between 0.80 and 0.88 are noted. However, the range of variation of regression coefficients, and of the intercepts and slopes, for the pan evaporation and the Meyer pan-size evaporation, is larger than that for the Morton pan-size evaporation. For example, the values of the intercept for the Meyer estimates are 34.9, 36.8 and -15.5 for the three months respectively, while for the Morton estimates, the comparable values are -16.8, -30.1 and -22.1 respectively (Table 2). We shall defer discussion of the exceptional value of the Meyer intercept for August to later.

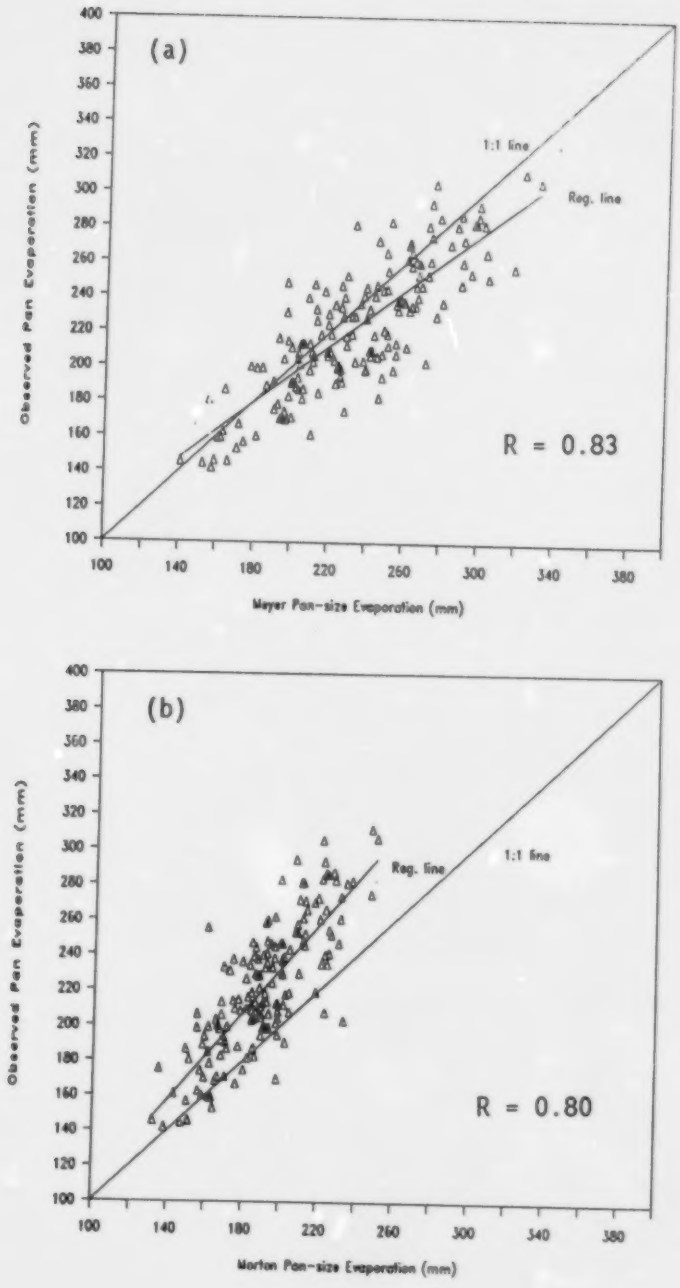


Figure 5: The relationship of monthly values between the evaporation pan observations and the pan-size evaporation estimates of (a) the Meyer model, and (b) the Morton model, in June, for each year of 1972-86, at each of the 11 stations on the Canadian Prairies

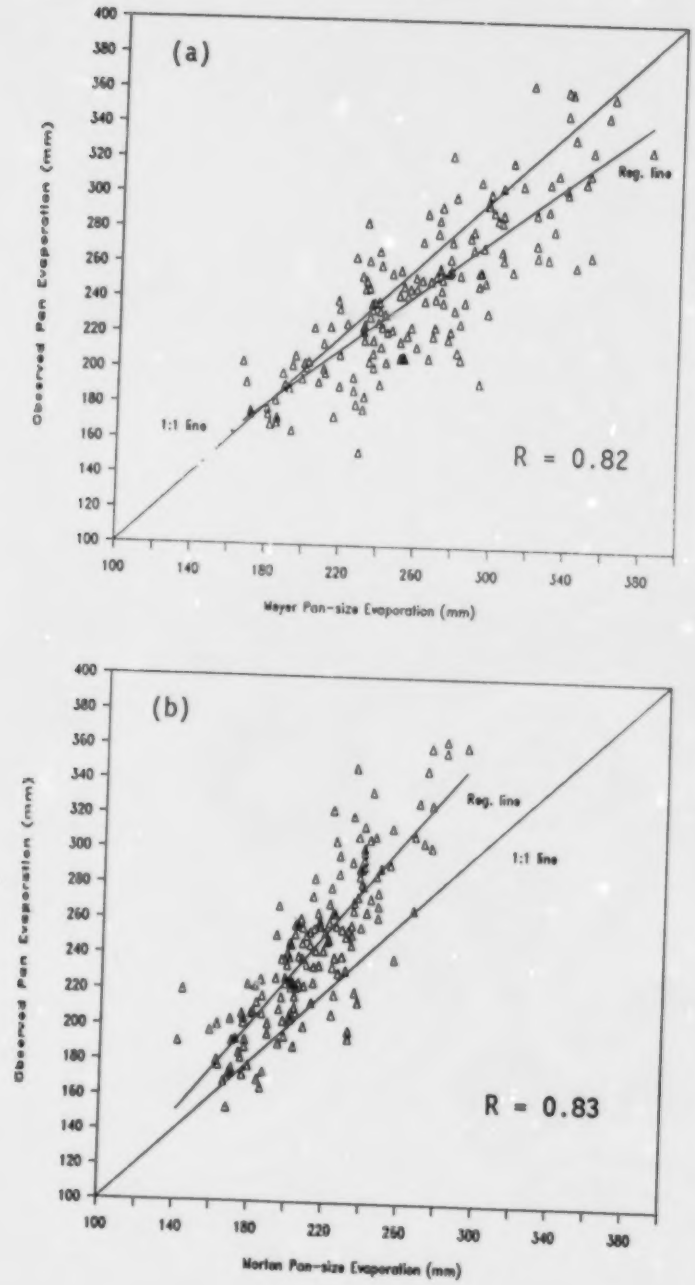


Figure 6: The relationship of monthly values between the evaporation pan observations and the pan-size evaporation estimates of (a) the Meyer model, and (b) the Morton model, in July, for each year of 1972-86, at each of the 11 stations on the Canadian Prairies.

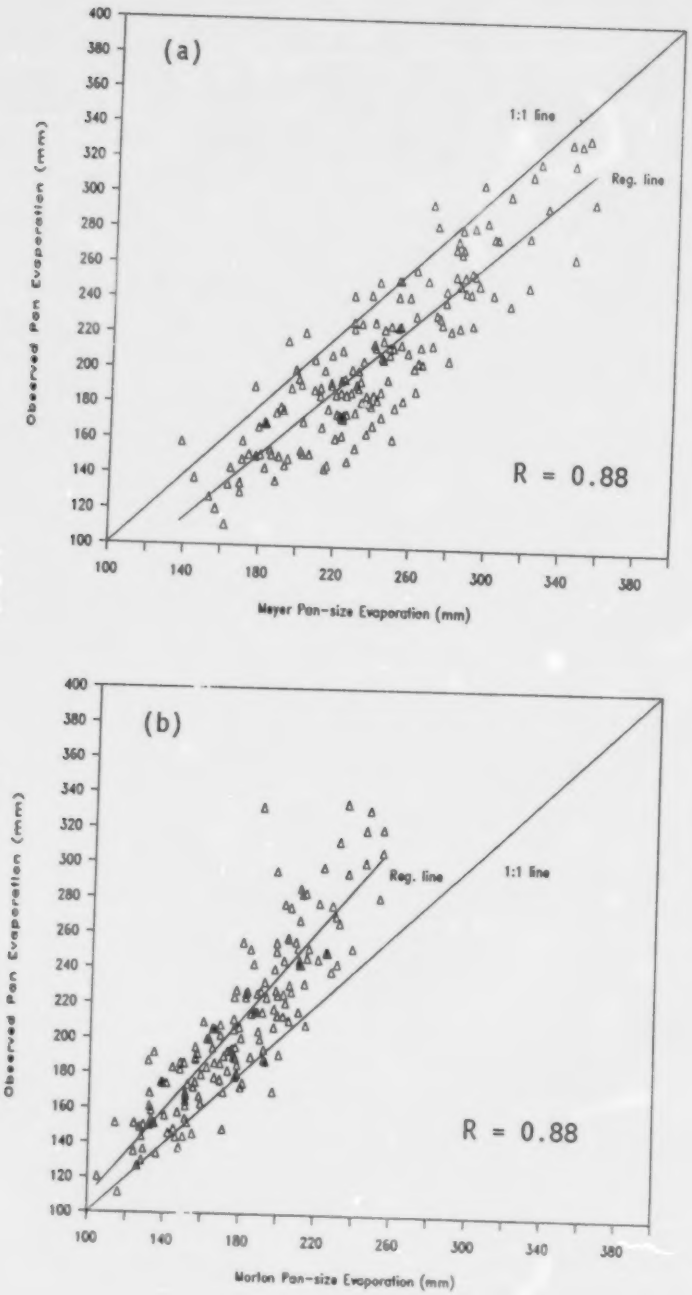


Figure 7: The relationship of monthly values between the evaporation pan observations and the pan-size evaporation estimates of (a) the Meyer model, and (b) the Morton model, in August, for each year of 1972-86, at each of the 11 stations on the Canadian Prairies.

3.2 Interpretation of Pan-size Intercomparisons

For the monthly pan-size evaporation estimates depicted in Figures 5-7, the accompanying Table 4, showing ranges of variation, indicates that for the Meyer model the maximum difference is 54.5% and ranges from -20.6% to +54.5%, and for the Morton model the maximum difference is 43.1% and ranges from -43.1% to +19.8%. Therefore, in Table 4, the maximum difference and the range in the Meyer model are higher than those in the Morton model. On the other hand, the mean differences in the Morton model are higher than those in the Meyer model excluding the August values (Table 4). Furthermore, Table 5 and Figure 8 demonstrate that, according to the distributions of the differences in the two models, the Meyer model appears to be slightly better than the Morton model. Table 5 indicates that, for the pan-size evaporation estimates, about 80% of the 495 computations of evaporation are within 20% of the evaporation pan measurements, for both the Meyer and the Morton models. However, for the Meyer model, more than 50% of the data points are within 10% of the pan observations, while for the Morton model, less than 40% of the data points are within 10% of the measured pan evaporation values. These observations are demonstrated visually in Figure 8.

Figure 9 shows the relationship between the individual monthly pan-size evaporation estimates from the Meyer and Morton models for the three months together. The correlation coefficient of 0.78 is relatively low, and the differences in estimated values of evaporation between the two

Table 4: The ranges of variation of Meyer (C = 13.8) and Morton pan-size evaporation estimates, compared with evaporation pan data, from June to August, 1972-86, at the 11 stations on the Canadian Prairies.

	Morton-Pan: $\Delta E_{PMT}/E_P$ (%)				Meyer-Pan: $\Delta E_{PMY}/E_P$ (%)			
	Max. (absolute)	Min.	Mean	Range	Max. (absolute)	Min.	Mean	Range
Long-term three-month average evaporation								
	20.1	0.9	-12.9	-20.1--0.9	20.2	0.4	8.7	-0.4-20.2
Annual three-month total evaporation								
	37.7	0.1	-12.9	-37.7-10.4	41.0	0.1	9.1	-13.1-41.0
Monthly evaporation								
June-August	43.1	0.1	-12.8	-43.1-19.8	54.5	0.0	9.3	-20.6-54.5
June	37.3	0.2	-12.9	-37.3-16.6	35.0	0.2	5.4	-20.6-35.0
July	35.0	0.4	-12.0	-35.0-19.8	51.6	0.1	7.2	-18.4-51.6
August	43.1	0.1	-13.4	-43.1-15.5	54.5	0.0	17.0	-12.0-54.5

Note: $\Delta E_{PMT} = E_{PMT} - E_P$.
$\Delta E_{PMY} = E_{PMY} - E_P$.

Table 5: The distribution of possible errors in pan-size evaporation estimates from Meyer (C = 13.8) and Morton models, compared with the evaporation pan data, based on 495 sets of monthly values, from June to August, 1972-86, at the 11 stations on the Canadian Prairies.

	Error Envelope (%)									
Data Points (%):	100	90	80	70	60	50	40	30	20	10
Meyer-Pan:										
$\Delta E_{PMY}/E_P$ (%)	54.5	28.0	20.5	15.9	12.7	9.9	7.5	5.1	3.6	1.8
Morton-Pan:										
$\Delta E_{PMT}/E_P$ (%)	43.1	23.1	20.0	18.0	15.8	13.2	10.8	8.7	6.0	2.9
Meyer-Pan/Morton-Pan:										
$\frac{\Delta E_{PMY}/E_P 6}{\Delta E_{PMT}/E_P}$	1.26	1.21	1.03	0.88	0.80	0.75	0.69	0.59	0.60	0.62

Note: $\Delta E_{PMT} = E_{PMT} - E_P$.
$\Delta E_{PMY} = E_{PMY} - E_P$.

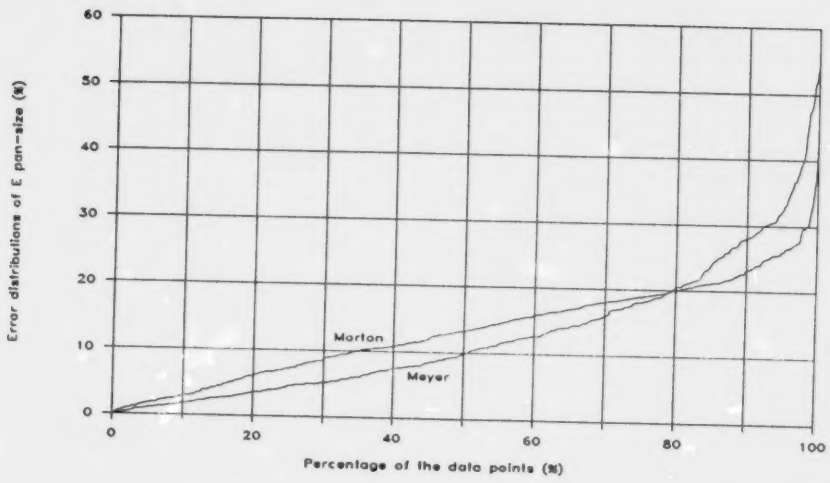


Figure 8: The distribution of possible errors in pan-size evaporation estimates from the Meyer and the Morton models compared with the evaporation pan data, from 495 sets of monthly values, from June to August, 1972-86, at the 11 stations on the Canadian Prairies.

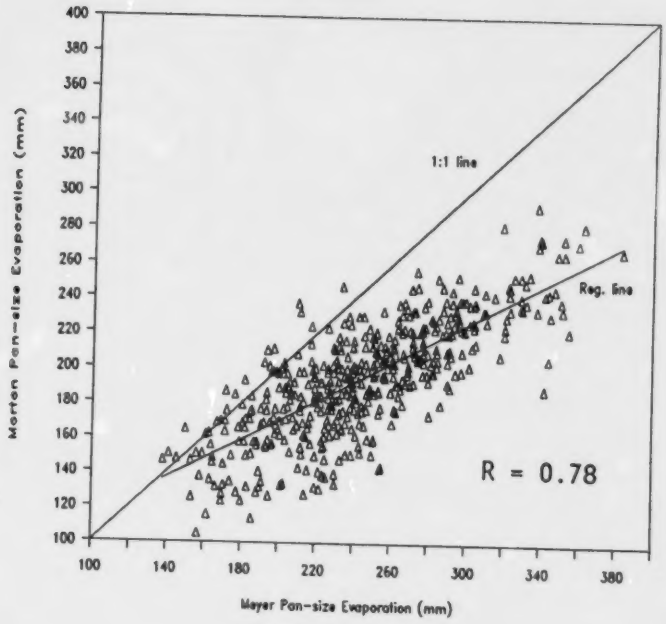


Figure 9: The relationship of monthly values between the Meyer and Morton pan-size evaporation estimates for each of the three months, June, July, and August, for each year of 1972-86, at each of the 11 stations on the Canadian Prairies.

models are relatively high. Thus, while there is good qualitative agreement between Meyer and Morton computations compared against pan observations (Figures 4-7), quantitative agreement and consistency between the two (Figure 9) are relatively low.

Temporal variations of pan-size evaporation at individual stations were also analyzed. Generally, the relationship previously shown in Table 3 represents temporal changes in the evaporation pan observations, as well as in the Meyer and Morton estimates. For example, at Broadview, the difference of the long-term three-month averages between the Meyer estimates and the evaporation pan observations, $(E_{PMY}-E_p)/E_p$, is -0.4%; i.e., the Meyer estimates are close to the observations at this relatively dry site (Table 3 and Figure 10a). The difference of the long-term three-month averages between the Morton estimates and the evaporation pan data, $(E_{PMT}-E_p)/E_p$, is -0.9% (Table 3 and Figure 10b). It appears that the Morton estimates represent the observations at this humid site. However, at some stations, the relationship appears to be more complicated and uncertain. A typical example is the relationship at Winnipeg. At this station, the mean differences are 4.6% for the Meyer estimates and -6.6% for the Morton estimates respectively, compared with evaporation pan observations (Table 3). A general observation from Figure 10 which may or may not be significant, is that for the period 1972-76, the Meyer estimates agree better with the evaporation pan observations, while for the period 1977-82, the Morton estimates provide a better representation of the evaporation pan observations. After 1982, the best estimate fluctuates

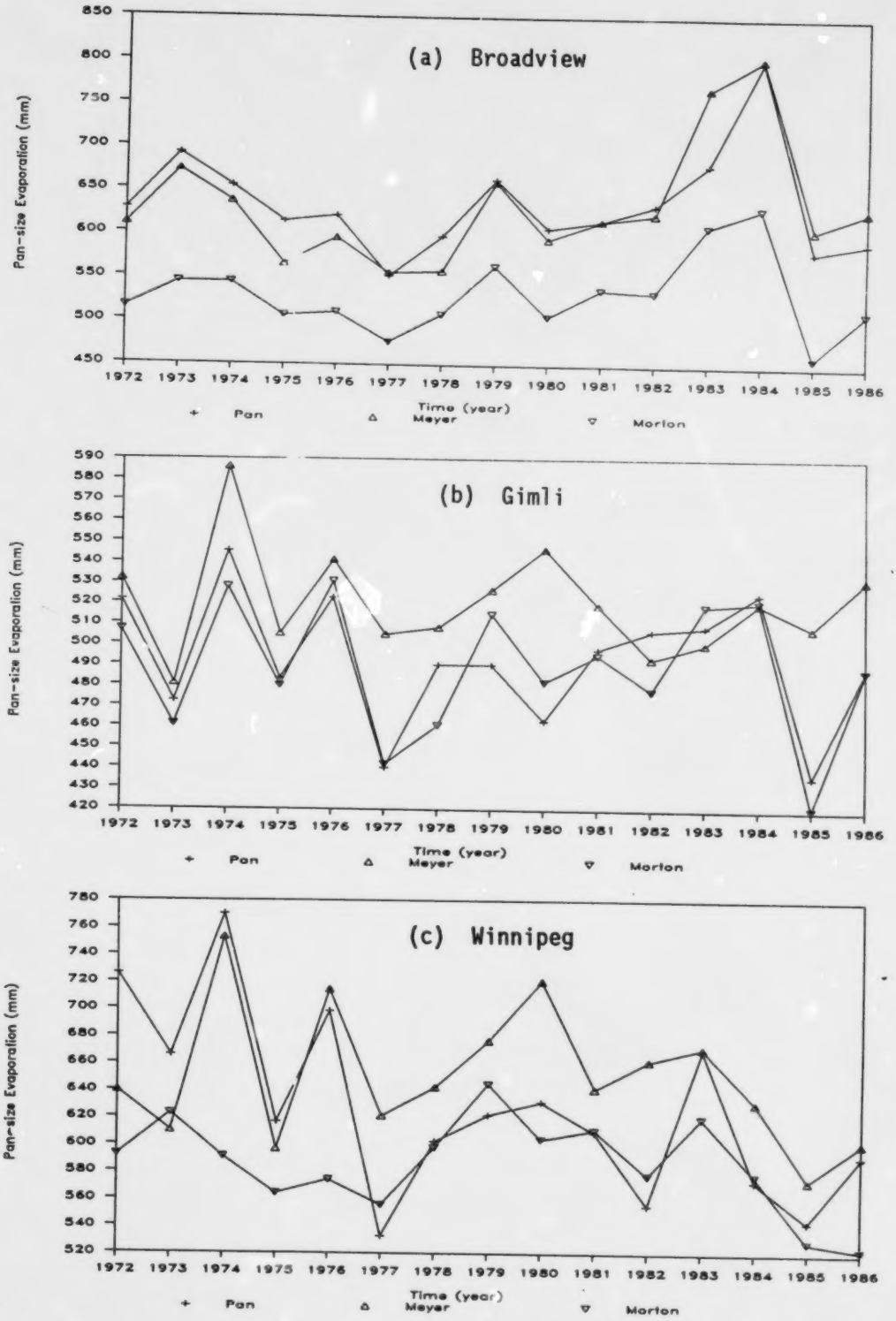
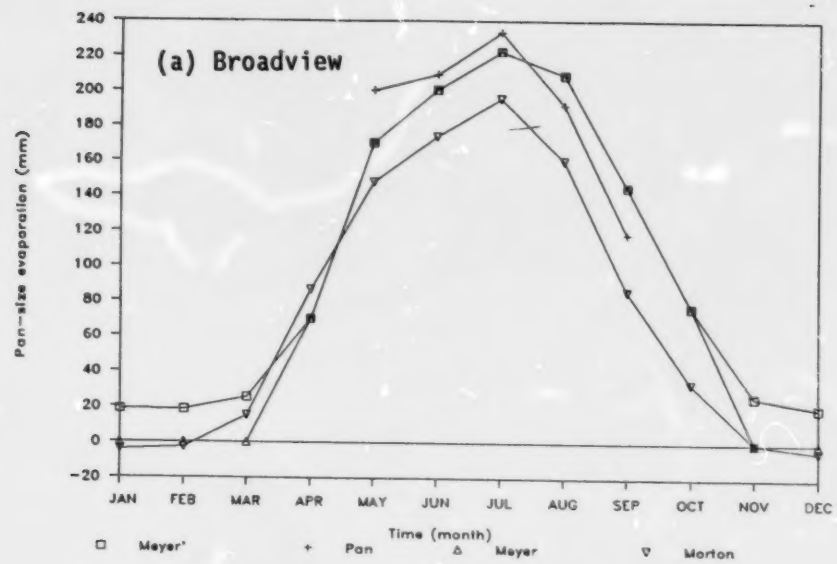


Figure 10: The annual variation of three-month total values of the evaporation pan observations, the Meyer and Morton pan-size evaporation estimates from June to August, 1972-86, at (a) Broadview, (b) Gimli, and (c) Winnipeg.

between the Meyer and Morton models (Figure 10c).

It was difficult to compare monthly distributions of pan and/or pan-size evaporation during a year for these Prairies locations because evaporation pan observations were not available for most of the months (October to April inclusive) in the year. Figure 11 shows the monthly distributions of long-term annual mean pan-size evaporation at Broadview and Gimli. The figure indicates that the temporal peak in the Meyer distribution lags behind that of the Morton distribution. Generally, prior to May, the Morton estimates are relatively higher than the Meyer estimates, and then the former is lower than the latter in the following months. This relationship is a representation of the general distribution for the 11 stations.

The long-term monthly averages of the available evaporation pan data were also plotted in Figure 11 for the two stations. Because of missing data, the May pan evaporation values are the average of 1972, 1976, 1977, 1980, 1981, 1985 and 1986 for Broadview, and the average of 1972, 1973, 1977, 1978 and 1980 for Gimli. For most data points, the distributions of the observations appears to lie between the estimates of the two models. Even so, on the one hand, the evaporation pan observations were not available for the winter period as mentioned above. On the other hand, the pan-size evaporation provided by the Meyer model was assumed to be zero when the calculated surface water temperature was equal to or less than zero during the winter period. Otherwise, the Meyer estimates for the



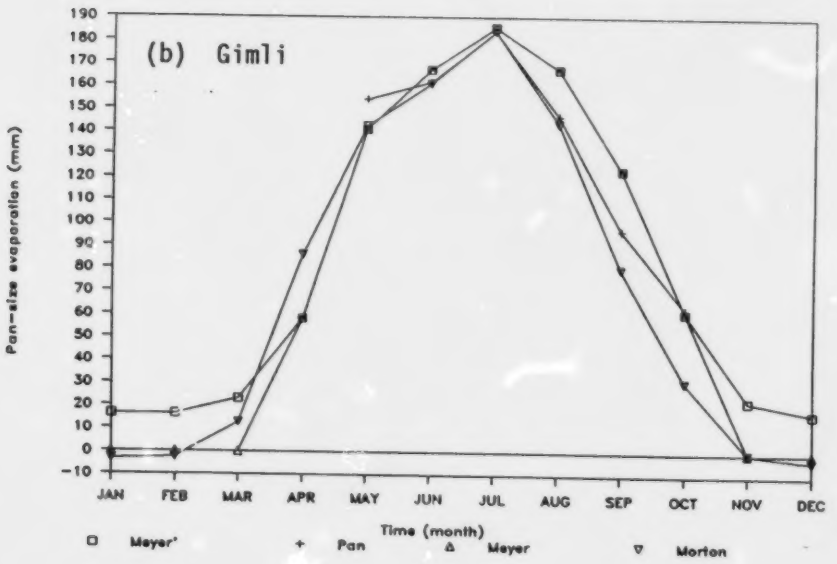


Figure 11: The monthly distribution of long-term annual pan-size evaporation estimates from the Meyer model and the Morton CRWE model, as well as the evaporation pan data for 1972-86, at (a) Broadview, and (b) Gimli. (Meyer' represents the pan-size evaporation "without" the limitation $E_{PMY}=0$ when $T_d \leq 0°C$).

winter period were significantly high if computed without this assumption (Figure 11). Therefore, a valid comparison during the winter period was not possible with these limited data for Prairie conditions.

The most sensitive factors affecting Meyer pan-size evaporation estimates are the Meyer evaporation coefficient, the lag between the air temperature and the surface water temperature, and the data transfer and/or modification techniques as described by Martin (1988).

The Meyer evaporation coefficient is a comprehensive factor which is purported to encompass variations due to the method of measuring vapor pressure, temperature and humidity, and the size and character of the water body. In the present study, a simple linear relation between the coefficients of pan and lake evaporation was assumed. For the three-month period, the ratio of the Meyer lake evaporation coefficient (C = 10.1) to the Meyer pan-size evaporation coefficient (C = 13.8) is 0.73; in other words, the pan evaporation coefficient is 0.73. However, the ratio of the evaporation pan observations to the Meyer lake evaporation estimates is about 0.80, or the "*actual*" pan evaporation coefficient is 0.80. These data indicate that if the Meyer lake evaporation estimates were assumed to represent true lake evaporation values, on average, then the Meyer pan-size evaporation coefficient should be about 12.6 instead of 13.8. Otherwise, the Meyer pan-size evaporation estimates might be 8.7% higher than the evaporation pan observations, based on the long-term three-month averages without considering other affecting factors. When the C-value

of 12.6 is used, the mean difference becomes -0.7% ranging from -9.1% to +9.7% for the long-term three-month averages. Obviously, if the original Meyer coefficient of 15 were used, the average Meyer pan-size evaporation estimates would be about another 10% higher than the average evaporation pan observations.

In the Meyer formulation, the heat storage in lakes or reservoirs is taken into account by using surface water temperature. However, when the same formulation is used to calculate pan-size evaporation, a simple proportional relation leads to the time lag in the modelled pan-size evaporation to the observed pan evaporation. As a result, our computed Meyer pan-size evaporation is higher than the observed average pan evaporation at most selected stations, as demonstrated by Figure 11. This effect is most significant in August, when the Meyer estimates are much higher than the evaporation pan observations, with an average difference of +17.0% and a range from zero to +54.5%.

The surface water temperature modification formulation (Equation 3), and the corresponding constants, were derived based on available data from May to October at 13 sites on the Prairies (Martin, 1988). Martin's version for surface water temperature modification may provide a more consistent and acceptable surface water temperature for the stations and months used in the present study, as compared with other studies. In previous studies, the surface water temperature was obtained from formulations containing only one constant for the whole year (e.g.,

Buckler, 1973; Wiens, 1978), or from a more limited database with different constants for each month, such as PPWB (1952).

The vapor adjusting formulation (Equation 4) was reported to be similar to Meyer's (1942) nomograph (Martin, 1988). We have therefore adopted Martin's formulation here.

In the wind speed transfer formulation (Equation 5), an exponent of 0.25 is used in the current study. This value was recommended by Buckler (1969) for application to Canadian Prairie areas which typically have few trees, and gentle, rolling terrain.

Undoubtedly, the original researchers derived these formulations by doing their best with available data, thus providing more reasonable and acceptable estimates compared with earlier versions. Even so, further studies on the formulations and parameters, such as surface water temperature transfer, wind speed adjustment and vapor pressure modification, are still needed. For example, it may prove useful to stratify statistics relating water temperature to mean air temperature based on some ratio of water body surface area to the total water volume, rather than attempting to use surface area alone or "shallow" versus "deep" lakes. Although the error involved in a single variable may be of insignificant order, the cumulative error from multiple sources may be significant.

In accordance with Morton's definition (Morton, 1983a, 1983b, 1986), the *pan-size* evaporation or *pan-size* wet-surface evaporation is the potential evaporation from a land surface, which is equivalent to U.S. Class A pan evaporation. This definition was used to verify the complementary relationship of *pan-size* evaporation and *lake-size* evaporation by using annual Class A pan coefficients from Lake Okeechobee in Florida, Lake Hefner in Oklahoma, and the Salton Sea in California (Morton 1983a, 1983b, 1986; Morton et al., 1985). Nevertheless, in this study, the pan-size evaporation estimates from the Morton CRWE model tend to be consistently lower than the evaporation pan observations at most selected stations. The differences between the long-term three-month averages from the Morton pan-size evaporation estimates and the evaporation pan observations for the selected stations range from -0.9% to -20.1% (see Tables 3 and 4). The consistently low values of Morton pan-size evaporation estimates impact on the hypothesis of the complementary relationship; that is, that the sum of potential and areal evapotranspiration is twice the wet-environment areal evapotranspiration; in other words, that the increase in the areal evapotranspiration is equal to the decrease in the potential evapotranspiration.

Morton's CRWE and CRLE models both produce reliable pan-size evaporation estimates for relatively humid conditions and low wind speed areas, but under-estimate pan-size evaporation for arid conditions and high wind speed areas on the Prairies, compared with the evaporation pan observations. For example, at Gimli, a relatively humid site with a mean

annual precipitation of 537.3 mm and mean monthly wind speed of 12.2 km hr^{-1}, the pan-size evaporation estimates and the evaporation pan observations are in excellent agreement, with a difference of only -4.3 mm, or -0.9%. On the other hand, at Swift Current, a relatively dry site with a mean annual precipitation of 366.0 mm and mean monthly wind speed of 19.7 km hr^{-1}, the difference between the estimated Morton pan-size evaporation and the measured pan evaporation is as high as -20% (Table 3).

As the Morton pan-size evaporation estimates are generally lower than the evaporation pan observations, especially in relatively arid areas, the pan-size evaporation in a completely dry land environment may not be twice the lake-size evaporation as defined by Morton (1983a, 1983b, 1986). In the case of areal evapotranspiration predictions, it would lead to an over-estimated areal evapotranspiration value, such as Ali and Mawdsley (1987) reported for Brutsaert and Stricker's (1979) advection-aridity model of the complementary relationship. Fortunately, the Morton CRAE model provided reliable areal evapotranspiration estimates within 10% of water budget estimates for over 140 river basins worldwide (Morton, 1983a). Furthermore, wet-environment areal evapotranspiration, another governing condition of areal evapotranspiration, is calculated by the modified Priestley and Taylor formula (Equation 10), and does not affect the potential evapotranspiration. Therefore, the relationship that the sum of the potential and areal evapotranspiration is twice the wet-environment areal evapotranspiration does not appear to exist in the conditions considered in this study. This same situation has been

reported by LeDrew (1979). An ideal modification for improvement of the Morton evaporation technique of complementary relationship has been proposed by Kovacs (1987), while a practical wind speed modification in Morton's potential evapotranspiration formulation has been used by Granger and Gray (1989).

In short, our results for pan-size evaporation simulations show that the Meyer model has a slight but consistent advantage over the Morton CRWE model, when evaluating against data from the U.S. Class A pan. This rather tenuous conclusion is based on the fact that the correlation coefficients for the pan data versus the Meyer estimates are slightly higher than those for the pan data versus the Morton estimates. By the same token, the mean percent differences between the pan data and the Meyer estimates (5-10%) are slightly lower than those between the pan data and the Morton estimates (generally about 13%), except for August in which the average pan-Meyer difference jumps to 17% (Table 4).

3.3 Comparative Results from China

It was desirable, if possible, to repeat some of these intercomparisons using an independent data set under a different set of environmental conditions. The availability of some climatological data from central China, including evaporation pan data, allowed a comparison of Morton estimates against pan observations. It should be noted that the pan in use in China is a 20-cm pan, compared with the 122-cm (4 ft) Class

A pan in use in North America, so that higher values of pan evaporation could be anticipated from this fact alone. Also, since no local empiric formulations for data transfer and modification in the Meyer formulation were available for these Chinese conditions, no Meyer estimates were attempted in this comparison.

The data were obtained for nine climatological stations in Shaanxi, China. The nine stations are located in the area between N32°50′ to N38°14′ and E106°15′ to E109°42′, extending across humid, semihumid and semiarid climatic zones. There are several classifications of climatic zones in China (Luo and Wang, 1987). In the present study, the classification using annual precipitation as a norm (Wang, 1983) is used. In Wang's classification, an area where the annual precipitation is less than 200 mm is classified as an arid zone, between 200 and 450 mm, a semiarid zone, from 450 to 650 mm, a semihumid zone, and greater than 650 mm, a humid zone.

Figure 12a presents the relationship between observed annual pan (20 cm in diameter) evaporation and the modelled annual Morton pan-size evaporation for these nine Chinese stations. Figure 12b shows monthly pan data and corresponding Morton pan-size estimates for each month and each station, averaged over the 10-year period, 1971-80. For annual evaporation, the correlation coefficient of linear regression is 0.97, while the standard error of estimated 20-cm pan evaporation, using the regression equation, is -12.9 mm. For monthly evaporation, the

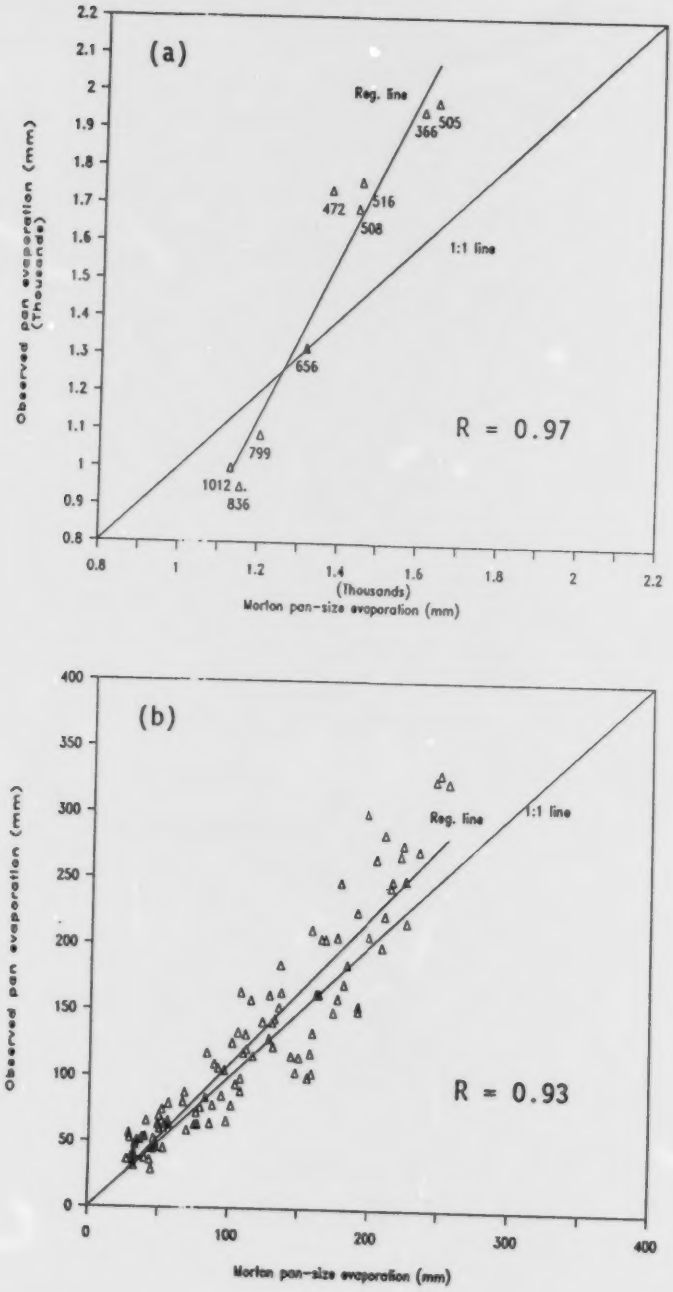


Figure 12: The relationship of the evaporation pan (20 cm in diameter) observations and the Morton CRWE model estimates: (a) long-term annual averages, and (b) monthly values, for 1971-80, at nine stations in Shaanxi, China. (The plotted values in (a) represent average annual precipitation).

correlation coefficient and standard error are 0.93 and 27.7 mm respectively. The comparative values of correlation coefficients for the 11 Canadian stations were 0.89 and 0.85 respectively, indicating that the correlation coefficients for the Chinese data are about 9% higher than those for the Canadian data. Therefore, the correlation relationship is very good between the 20-cm pan data and the Morton model estimates. Evaporation from the 20-cm pan should be much higher than the 122-cm U.S. Class A pan evaporation. However, our Morton pan-size evaporation estimates (e.g. Figure 12a), which, by definition, are purported to represent Class A pan values, show that in the humid area the Morton pan-size evaporation estimates are even higher than the 20-cm pan observations. As such, the Morton model may over-estimate potential evaporation for the humid area, and under-estimate potential evaporation for the relatively arid area in the Chinese environment.

By employing the Chinese data, we recognize that it is not possible to used the Meyer method to calculate open water evaporation for the areas where the data transfer and modification formulations and relative constants are not available. Theoretically, the Morton evaporation method is easily applicable anywhere in the world, using only routinely observed climatological data without locally optimized coefficients. However, the disagreement in Morton's definition and our results for pan-size evaporation for these Chinese data, indicates again that the complementary relationship of evaporation may not be valid.

3.4 Lake-size Intercomparisons

Unlike the pan-size intercomparison, to compare lake-size evaporation estimates, there was no control data set against which to compare the results in this study. To get around this problem, an attempt was made to create a control data set by manually interpolating values of lake evaporation from the Mean Annual Lake Evaporation map prepared by Fisheries and Environment Canada (1978). We recognize that this map was prepared using pan observations, supplemented by computed pan evaporation values using the Christiansen (1966) method, and then the pan data were converted to lake evaporation using the Kohler et al. (1955) method. However, the combined processes of map contouring plus our interpolation represent a form of data filtering, which, if they do not smooth out errors, at least might provide a more uniform data base.

Using this somewhat inappropriate control data set for lake evaporation, only some limited intercomparisons of *lake-size* or "shallow" lake evaporation were carried out, applying the Meyer model with C = 10.1, and the Morton CRWE and/or CRLE models. The Meyer and Morton lake evaporation estimates were both compared against the interpolated values from the Mean Annual Lake Evaporation map.

The relationship between the Meyer and Morton estimates for evaporation from lakes and reservoirs is similar only in a gross way to the relationship for the pan-size evaporation estimates. That is, the

Meyer model tends to over-estimate and the Morton model tends to under-estimate lake evaporation, just as they do for pan evaporation. However, the correlation coefficients for the interpolated map values versus the Meyer and Morton estimates are much lower, at 0.65 and 0.50 respectively, compared with pan-size evaporation correlations. The standard errors are 88.3 and 100.5 mm, respectively. The relationships of the map versus the two models' estimates are shown in Figure 13.

The correlation between the Meyer and Morton lake evaporation estimates is higher, as one should expect from the pan-size evaporation intercomparison, with a correlation coefficient of 0.85 (Figure 14a). The standard error of the Morton estimates from the regression equation is 28.0 mm. However, differences in the lake evaporation estimates between the two models are significantly high (Table 6). Even so, there is an exception. At Gimli, the long-term annual averages are 675.9 mm using the Morton CRWE model, and 661.9 mm using the Meyer model, based on the assumption, $E_{LTY} = 0$, when $T_w \leq 0$ °C. The difference of the averages for the two models at this station is only 2.1%. However, the relationship between the annual estimates of the two models for individual years at Gimli is extremely poor with a correlation coefficient of only 0.32. Figure 14b shows the temporal distribution of annual lake-size evaporation estimates for the two models.

The monthly distributions of the long-term annual average evaporation for all stations are the same as those of the pan-size

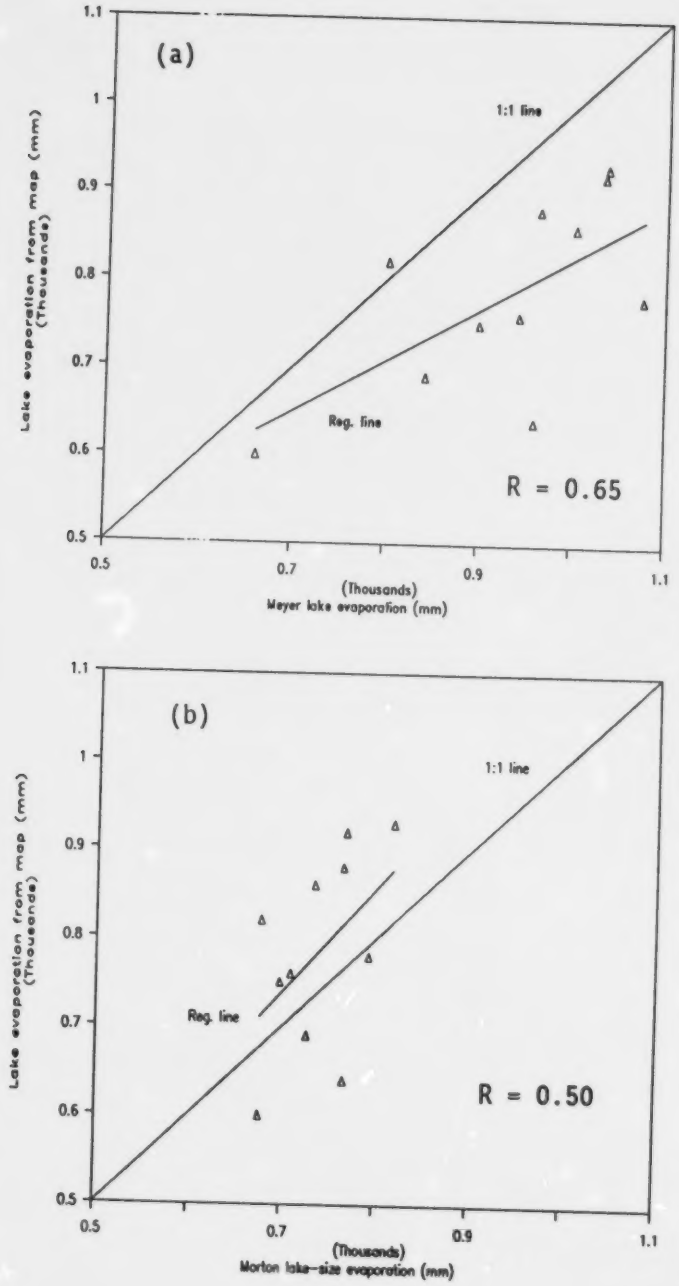


Figure 13: The relationship of long-term annual averages between the interpolated map values and (a) the Meyer lake-size evaporation estimates, and (b) the Morton lake-size evaporation estimates, for each of the 11 stations on the Canadian Prairies.

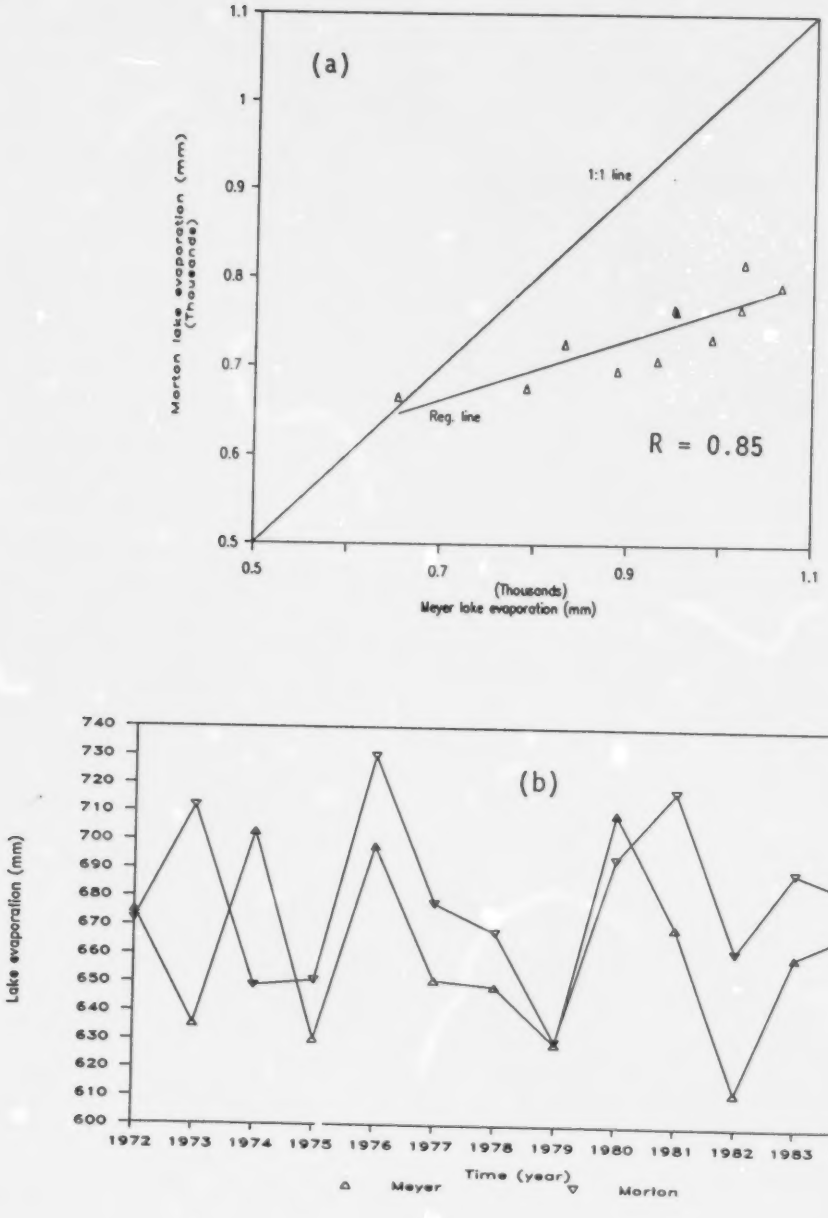


Figure 14: (a) the relationship of long-term annual average lake-size evaporation estimates between the Meyer and Morton models for the 15 years, at each of the 11 stations on the Canadian Praries, (b) the temporal variation of annual lake-size evaporation of the Meyer and Morton CRWE model at Gimli.

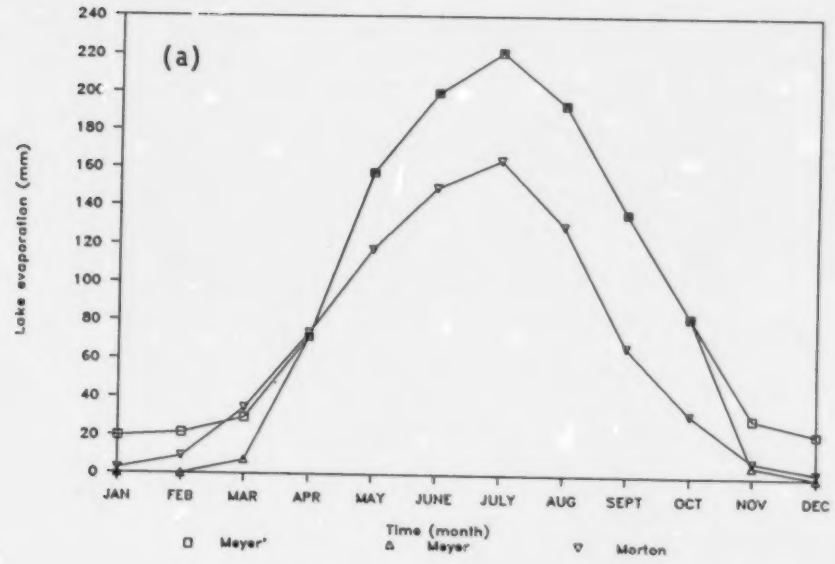
Table 6: Intercomparison of mean annual lake evaporation from the interpolated map values, Meyer (C = 10.1) and Morton lake evaporation models for the 11 stations on the Canadian Prairies.

Station name	Map E_{LMP} (mm)	Morton E_{LMT} (mm)	Meyer E_{LMY} (mm)	Morton-Map $\Delta E_{LMT}/E_{LMP}$ (%)	Meyer-Map $\Delta E_{LMY}/E_{LMP}$ (%)	Morton-Meyer $\Delta E_{LTY}/E_{LMT}$ (%)
Calgary	640	766.5	960.0	19.8	50.0	-25.2
Lethbridge	780	792.3	1075.7	1.6	37.9	-35.8
Medicine Hat	930	818.0	1035.4	-12.0	11.3	-26.6
Broadview	820	676.6	801.3	-17.5	-2.3	-18.4
Estevan	880	764.3	963.4	-13.1	9.5	-26.0
Regina	860	733.7	1002.0	-14.7	16.5	-36.6
Saskatoon	760	708.5	942.5	-6.8	24.0	-33.0
Swift Current	920	767.0	1032.4	-16.6	12.2	-34.6
Yorkton	750	697.0	899.6	-7.1	19.9	-29.1
Gimli	600	675.9	661.9	12.6	10.3	2.1
Winnipeg	690	726.5	843.0	5.3	22.2	-16.0
Mean	780	738.8	928.8	-4.4	19.2	-25.4

Note:
E_{LMT} = Morton lake-size evaporation estimates.
E_{LMY} = Meyer lake-size evaporation estimates.
E_{LMP} = Lake evaporation interpolations from the Mean Annual Lake Evaporation map provided by Fisheries and Environment Canada (1978).
$\Delta E_{LMT} = E_{LMT} - E_{LMP}$.
$\Delta E_{LMY} = E_{LMY} - E_{LMP}$.
$\Delta E_{LTY} = E_{LMT} - E_{LMY}$.

evaporation, since the ratio of the Meyer pan evaporation coefficient to the Meyer lake evaporation coefficient is assumed to be linear, and the CRWE model does not consider the effects of heat storage in the lake. This situation is changed by using the CRLE model, which does include the heat storage effect on the evaporation from lakes. For example, on Henderson Lake at Lethbridge that has a mean depth of 3.4 m (Wiens, 1978), the monthly distribution of the long-term annual average lake evaporation estimates from the CRWE model (Figure 15a) is different from that from the CRLE model (Figure 15b). In Figure 15a, the distribution of the Meyer model estimates appears to lag behind that of the Morton CRWE model estimates. In Figure 15b, the distribution of the CRLE model estimates appears to lag behind that of the Meyer model estimates, although the difference of the long-term annual mean lake evaporation between the CRWE and the CRLE models is only 4.6 mm. In fact, by assuming various lake depths and using the input data for Medicine Hat, it was found that, for lake depths between two and three meters, the temporal distributions of the Meyer estimates and the Morton estimates are quite similar, at least during the high evaporative months, without taking into account effects of salinity.

Obviously, for estimating evaporation from lakes and reservoirs, it is difficult to determine which of the two models, the Meyer and Morton models, is more acceptable in the Prairie environment, especially when using the Mean Annual Lake Evaporation map compiled by Fisheries and Environment Canada (1978). The linear correlations of the mean annual



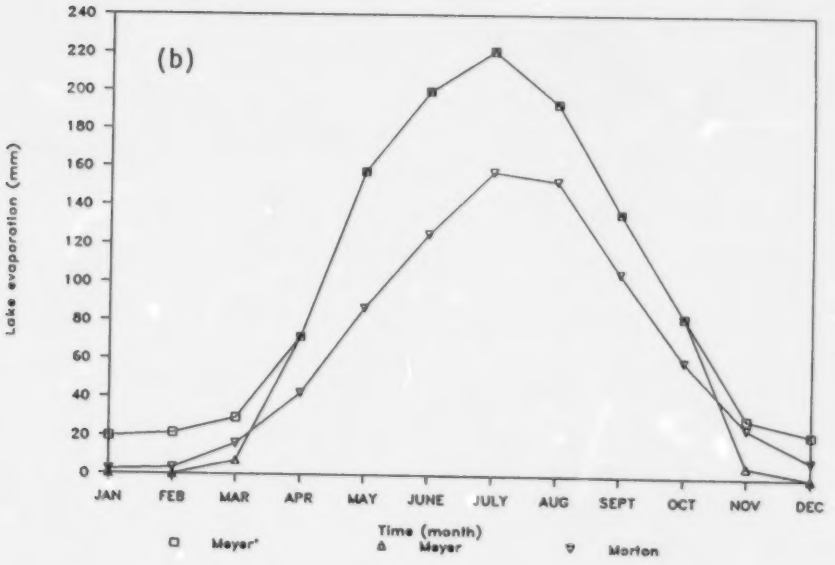


Figure 15: The monthly distribution of long-term mean annual lake-size evaporation from the Meyer and Morton CRWE models with (a) lake depth d = 0, and (b) d = 3.4 m, for 1972-86, from Henderson Lake on the Canadian Prairies. (Meyer' represents the lake-size evaporation without the limitation $E_{PNY}=0$ when $T_w \leq 0°C$).

lake evaporation for the map versus each of the two models are low, especially in the case for the Morton model. The correlation coefficient for the map-Meyer relationship is 0.12 higher than that for the map-Morton relationship. On the other hand, the mean difference between the map and the Morton model is -4.7%, ranging from -17.5% to +19.8%, while for the map versus the Meyer model, the mean difference is as high as 19.2%, ranging from -2.3% to +50.0% (Table 6). In addition, the map was compiled by using estimated lake evaporation values obtained from the Christiansen (1966) method with some modifications, and from the Kohler et al. (1955) method (Fisheries and Environment Canada, 1978), using climatological and pan evaporation data during the period 1957-66. However, the period involved in the present study is 1972-86. Therefore, it is unavoidable in this limited analysis that some uncertainties were involved in the map-Meyer and map-Morton lake evaporation relationships.

By adopting the Morton estimates as a "*control*" data set, the mean difference is -25.4% for the Morton estimates versus the Meyer estimates ($T_w \leq 0$ °C, $E_{LMY} = 0$), with a maximum difference of -36.6% at Regina and a minimum difference of +2.1% at Gimli (Table 6). At most of the selected stations, the Meyer estimates are much higher than those from the Morton model. Because there are no available lake evaporation data for the assumed lakes at the selected stations, it is not possible to evaluate the differences in detail in the present study. Therefore, only the following general type of error analysis could be performed.

3.5 Error Sources in Lake Evaporation Computations

In the Meyer model, the Meyer evaporation coefficient is a major factor affecting the lake evaporation estimates. The Meyer formula was developed for a more humid U.S. environment, so that it is questionable whether it is easily transferable to and equally valid for the Canadian Prairies. In comparison with the Mean Annual Lake Evaporation map of Fisheries and Environment Canada (1978), the Meyer lake evaporation estimates are significantly higher than those on the map at most stations, such as at Calgary, the Meyer estimate is 960.0 mm, while the value on the map is approximately 640 mm. If a relatively low coefficient (less than 10.1) was used, the results might be more reasonable and acceptable. In fact, according to Meyer (1942), the evaporation coefficient varies with both the installation height of thermometers and the mean air vapor pressure from April to August at the stations. In particular, Meyer (1942) pointed out that the evaporation coefficient should be reduced for the following areas: (1) arid areas in which the mean of morning and evening vapor pressure is less than the true value for the day, and (2) areas in which the summer water temperature appears to be somewhat lower than the air temperature, instead of higher. For example, for Yuma, Phoenix, Roswell, El Paso and Fresno, the coefficient was reduced by about 10% (Meyer, 1942). If the evaporation coefficient in the relative arid areas on the Prairies was reduced by 10%, the ratio of the Meyer lake evaporation to the pan-size evaporation would be 0.72, which is close to the commonly accepted pan evaporation coefficient used by McKay and

Stichling (1961) and Buckler and Quine (1971), and some improvement in accuracy in the Meyer lake evaporation estimates might be possible.

A major flaw in Morton's model appears to be the lack of a wind function, although we have no quantitative information to support this statement. Still, wind is a significant effect, especially on the windy Prairies, because of its ventilating effect of removing evaporated moisture and allowing more evaporation (drying) to lake place. Its effect can be estimated from Meyer's formulation.

It is also questionable whether the wind function in the Meyer formula is suitable for the Canadian Prairie environment, since it is the main difference between the Meyer and Morton lake evaporation models and has a significant effect on the Meyer estimates. For example, for the 11 Prairie stations, monthly wind speed varies from 8.6 to 33.1 km hr^{-1}. In other words, the wind function in the Meyer model changes from 1.5 to 3.1, that is, the Meyer open water evaporation estimates can be doubled by the wind function alone. This in itself does not make the technique inaccurate, since wind is known to have a strong ventilating and drying effect on moisture. However, it implies that careful sensitivity tests are necessary to establish appropriate empirical functions at each new location, and to our knowledge, this has not been done for the Prairies.

The estimation of surface water temperature is another error source in Meyer lake evaporation estimates. For instance, using Martin's (1988)

data (his Figure 6), the differences of the calculated surface water temperatures from the measured values were as much as to ±3.5 °C. This can lead to an error of more than ±30% in the Meyer evaporation estimates. Buckler and Quine (1971) reported that if the actual water temperature was available and a coefficient of 10 was used, the Meyer formula could produce a seasonal lake evaporation estimate within 5% of the water balance estimate.

Another problem in using the Meyer formula is the effect of elevation on lake evaporation. Meyer (1942) reported that the computed evaporation from small lakes and reservoirs in the United States was increased by about 1% for every 300 m (1000 ft) in elevation due to the effect of the change in barometric pressure. This modification has since been used on the Prairies (PPWB, 1952; Berry and Stichling, 1954; Buckler, 1973; Martin, 1987, 1988). However, Ferguson and Louie (1974) pointed out that mean annual lake evaporation actually decreased (rather than an increase) by approximately 7% per 300 m of elevation above a base elevation of 300 m (ASL). Their estimate was based on pan evaporation data. This result was incorporated in the data used to compile the Canadian Mean Annual Lake Evaporation map (Fisheries and Environment Canada, 1978). Although the increased amount of Meyer lake evaporation due to the change in elevation is less than 4% of the total value for the conditions involved in our study, the difference may be over 20%, compared with the lake evaporation estimates using the Ferguson and Louie (1974) modification. For instance, at Calgary, the mean annual lake evaporation

from the Meyer model, applying Meyer's elevation modification, is 960 mm. This value is reduced to 757.5 mm when the Ferguson and Louie elevation modification is applied. If the latter modification is correct, then the version of Meyer used in our analysis over-estimated lake evaporation by 27% for Calgary. Because this adds a further uncertainty of about ±25% in Meyer estimates, the effect of elevation on lake evaporation in the Meyer formula needs to be investigated in detail. This particular error source is not a problem in Morton's formulation, which is based on different physics, essentially an energy balance.

Another source of error in the Meyer model lies in the determination of lake evaporation when the calculated surface water temperature is equal to or less than zero. It is evident that evaporation does occur during "*winter time*". It is well-known, for example, that evaporation from the Great Lakes, or offshore the east coast of Canada, is maximum during early winter when below-freezing air passes over relatively warm open water. The Meyer formulation does not account for these extremes of evaporation. Another winter evaporation peak occurs in late-winter or early-spring, when most of the snow and ice cover on lakes and reservoirs on the Prairies may be melted, accompanied by increased evaporation. Therefore, it is not reasonable to assume that evaporation is zero when the surface water temperature is equal to or less than zero. In fact, it can be maximum around this time. Therefore, more attention should be paid to the various data adjustment and transfer techniques, especially to the surface water temperature and its interaction with the ambient air

temperature.

The Morton lake evaporation technique was evaluated by Andersen and Jobson (1982). By using the "1979 version" of the Morton CRLE model, Andersen and Jobson (1983) reported that, for 28 lakes in the United States, the average difference of the Morton lake evaporation estimates to the reported values, determined from measurements on each lake, was 19.8%. The differences for individual lakes ranged from -30.5% (Lake Colorado City) to as high as +77.4% (Hungry Horse Reservoir), so that some of the reported lake evaporation values were understandably questioned by Morton (1983c). The average difference for the eight lakes involved in Andersen and Jobson's (1982, 1983) study, and also used by Morton (1979), was only 6.3% compared with water budget values. Morton's CRLE model (1983 version) was used for lake evaporation calculations for 17 lakes, and the lake evaporation estimates were all within 10% of water budget results (Morton, 1986).

In short, for operational applications of the Meyer formulation, further rationalization of the various data transfer and modification techniques are required. In particular, we have noted the following sources of error in the Meyer and Morton techniques for computing evaporation:

1) the subjective choice of the empiric constant in Meyer's technique;
2) the lack of a wind function in Morton's technique, and lack of sensitivity tests for Canadian Prairie conditions in Meyer's wind

function;

3) the use of (a) estimated water temperatures in Meyer's technique or lack of actual water temperatures, (b) "sub-surface" rather than water temperatures in some field data;
4) the validity of Morton's radiation term;
5) the validity of various adjustments for elevation used in the Meyer formulation in different studies;
6) the assumption of "no evaporation" when water temperatures are ≤ 0 °C in Meyer's formulation.

The net uncertainty in Meyer or Morton lake evaporation computations is difficult to establish in this study, due to the above error sources and the lack of a "control" lake evaporation data set. However, our estimate of the net uncertainty in a given monthly estimate of open water evaporation, using standard climatological data, is ±50% for either technique. We will attempt to resolve this further in the following section by re-visiting a more localized "control" water balance data set used in the Weyburn Reservoir evaporation studies.

3.6 Comparative Results from Weyburn Reservoir Studies

There have been few studies of open water evaporation in Canada where the water balance was accurately known. One of the more credible studies conducted was the Weyburn Reservoir experiment of 1960-61 (McKay and Stichling, 1961; McKay, 1962). This particular reservoir was chosen

for investigation because the ground water component was considered to be negligible (McKay and Stichling, 1961). However, visual evidence of seepage below the dam was noted later (McKay, 1962; Buckler and Quine, 1971). Estimates of the seepage were made during winter conditions by assuming zero evaporation and attributing the residual in the water balance equation to ground water alone (McKay, 1962). McKay thereby estimated the winter seepage out of the reservoir to be only 2% of evaporation, and suggested that the summer-time estimate would not be more than double this (4%).

However, Buckler and Quine (1971), using Weyburn Reservoir data for 1965-67, deduced that the winter seepage was a net '*inflow*' rather than '*outflow*' during 15 of 18 periods tested during 1965-66, with the average inflow being 5 mm $mo.^{-1}$ (0.0085 ft/5 days). This is equivalent to almost 10% of the June water balance evaporation estimated by McKay (1962). A further complication is that Buckler and Quine's (1971) estimates of seepage for the following winter (1966-67) showed a net *inflow* during only 2 of 13 periods, the remaining periods indicating either net *outflow* or zero flux. The average seepage was a net outflow of about 25 mm $mo.^{-1}$ (0.0078 ft/ 3 days), or 13% of McKay's June evaporation estimates. Therefore, the total uncertainty in evaporation estimates due to *winter-time* ground water uncertainties alone is of the order of ±15% (2% and 13%, inflow or outflow) for these Weyburn Reservoir data.

Since these represent only average values of seepage, the maximum

deviations, and therefore the uncertainty in evaporation estimates due only to ground water uncertainty, would have been higher. Moreover, McKay's (1962) estimate of summer-time seepage being double the winter-time estimates, suggests that the net *summer-time* uncertainty in evaporation estimates due to measurement uncertainties and natural fluctuations in ground water is of the order of ±30%. Indeed, Buckler and Quine (1971) provide two factors which may account for the fluctuations between positive and negative seepage: (1) a gradual penetration of frost during some winters to a sufficient depth to stop the flow of ground water into the reservoir, while allowing seepage at a greater depth, and (2) fluctuations in the water table between dry and wet years.

In addition, other error sources, which presumably were not accounted for in these Weyburn water balance evaporation estimates, are either noted by or can be deduced from the McKay and Stichling (1961), McKay (1962), and Buckler and Quine (1971) studies. These include inadequate metering of pumped water at the Weyburn filtration plant, additional seepage at the dam head itself, and uncertainty in the values of estimated precipitation and surface water flow.

Since the Weyburn studies rank among the better documented ones in Canada to date, we therefore reproduce some of McKay's (1962) results here in order to compare with our limited analysis using climatological data. Table 7 summarizes McKay's results and compares these with the current climatological estimates. Our emphasis here is on the ratios of Meyer

Table 7: Contrasting intercomparison of Pan and Meyer open water evaporation estimates using (a) real data from a field experiment at Weyburn Reservoir (after McKay, 1962), and (b) averaged results for hypothetical reservoirs from 1972-86 climatological data from 11 Prairie stations.

	(a) Weyburn Reservoir - 1961 (after McKay, 1962)				(b) Average of 11 Prairie stations - 1972-86			
	June	July	Aug.	Totals	June	July	Aug.	Totals
1. Pan observations								
a) Pan evaporation (mm)	272	274	234	780	222	245	208	675
b) 0.72[1] × Pan (mm) (lake evap.)	196	197	168	562	160	176	150	486
2. Water balance estimates								
a) Evaporation (mm)	185	188	201	574	-	-	-	-
b) Inferred pan coeff.	0.68	0.69	0.86	0.74	-	-	-	-
c) Ratio, water balance to 0.72 Pan	0.94	0.95	1.20	1.02	-	-	-	-
3. Meyer Computations								
a) for C = 11.0 (mm)	198	185	175	558	190	208	191	589
b) Correlations with pan observations	-	-	-	-	0.83	0.82	0.88	0.85
c) Ratio to .72 pan	1.01	0.94	1.04	0.99	1.19	1.18	1.27	1.21
d) Inferred Meyer Const. for lake evaporation (based on 0.72 pan)	10.9	11.7	10.6	11.1	9.3	9.3	8.6	9.1

[1] McKay (1962) used a coefficient of 0.72 to convert pan evaporation to lake evaporation.

estimates to pan data. Of course, Morton's complementary relationship model, first described by Morton (1965), was not available at the time of McKay's work. We emphasize that the Weyburn data in Table 7 represent only a single year's data from an actual field experiment over open water, and are from a single year, whereas our data are for hypothetical open water conditions; that is, we are using climatological data averaged over 15 years for each month, which are further averaged for 11 climatological stations. Also, McKay used actual water temperatures in the Meyer computations, while our data must employ an estimate of the water temperature (of a fictitious water body) based on a relation with mean monthly air temperatures as described by Martin (1988). McKay's (1962) results are shown without adjustments for the problem areas noted above.

In spite of the different data bases applied here, the monthly values of both pan and Meyer evaporation estimates are comparable in magnitude. The average 1972-86 climatological three-month totals of pan evaporation (675 mm) are within 15% of the Weyburn Reservoir totals (780 mm). Similarly, differences in the totals obtained for Meyer estimates are less than 10%, 589 mm for the climatological averages, and 558 mm for the Weyburn three-month totals. It remains to determine just how coincidental even this degree of agreement is.

One reason for comparing these two different data bases was to determine any biases between pan and Meyer (or other) estimates which

might increase confidence in the use of these methods. For example, McKay (1962) indicated that the Meyer formula and Class A pan gave "*acceptable estimates of seasonal evaporation*". In his analysis, both were "*within 2% of that obtained by the water budget*". He further estimated that "*the water budget had a probable error of about 10%*". The obvious deduction for the reader is that the uncertainty in monthly or seasonal evaporation values from either pan or Meyer estimates is no more than 12%!

Furthermore, Buckler and Quine (1972), while noting the additional sources of error in ground water estimates, still concluded that "*it does not appear necessary to measure the surface water temperature for use in Meyer's equation*". That is, they felt that an estimate of water temperature from mean monthly air temperatures was adequate. We would contend that this could be a dangerous assumption, since an error of 1 °C in water temperature contributes almost a 10% error in evaporation in Meyer's formula.

The above assumptions do not appear valid according to Table 7. We note that the ratio of Meyer evaporation estimates (using C = 11.0) to pan estimates for the Weyburn study was 0.99, while for our climatological data, this ratio is 1.21. Of course, one could argue that different Meyer constants should be used at each site. But that is exactly the point we would make here: that the use of the Meyer formulation really requires a more stringent definition of this elusive empiric constant, and that we are unable to determine any bias in our analysis which would improve our

confidence in these comparative results.

These factors from the Weyburn studies alone illustrate the logistical problems associated with water balance estimates of evaporation, where there are no controls on ground and surface water flows. Such problems are not insurmountable. For example, hydrologic measures of ground water during an experiment would at least indicate whether one was dealing with inflow or outflow, and the approximate magnitude of the water gain or loss. However, for a scientific experiment, where accurate estimates of evaporation, and hence of the water balance, are required as *measurement standards*, realistically one needs to *control* the ground water flow. This might be accomplished using a lined reservoir, where the ground water flow is theoretically reduced to zero. However, the cost of such a lined reservoir may be prohibitive, and there are no guarantees that the lining will not develop leaks at some stage. For this reason, ground water measurements should be an essential part of any field experiment involving evaporation within a water budget study.

3.7 Meyer-Morton Compromise

As mentioned above, in using Martin's (1988) version, the Meyer open water evaporation estimates are consistently higher than those obtained by using other methods, including the Morton method, the evaporation pan, the lake evaporation map, and other reported results such as those from

McKay and Stichling (1961). On the other hand, the pan-size evaporation estimates from the Morton model are consistently low compared with the evaporation pan observations and the Meyer pan-size evaporation estimates. The Morton lake-size evaporation estimates are also relatively low compared with the interpolated map values from the Mean Annual Lake Evaporation map at most of the selected stations. Thus, an obvious compromise in this study was to compute a simple average of pan-size values from the Meyer and Morton models. The resulting compromise provided much better agreement with the evaporation pan data than either model alone. This is partly demonstrated in Figure 16a.

For the six pairs of correlation coefficients in Table 2, the corresponding correlation coefficients for the Meyer-Morton compromise data, relative to the evaporation pan observations, are 0.93, 0.88, 0.90, 0.86, 0.87 and 0.92, respectively. On average, the coefficients are 5% higher than those from individual pan-Meyer and pan-Morton correlations. The mean slope of the linear regressions is 1.10, ranging from 0.99 for long-term three-month averages to 1.21 for August values. The linear regression best-fit line in Figure 16a, relating evaporation pan data to the Meyer-Morton compromise values, is almost coincidental with the one-to-one line; i.e., the slope is 0.99.

However, for lake evaporation, the correlation coefficient for the interpolated map values versus the Meyer-Morton averages is only 0.63. Despite this poor correlation, the slope of the regression line, 0.85, is

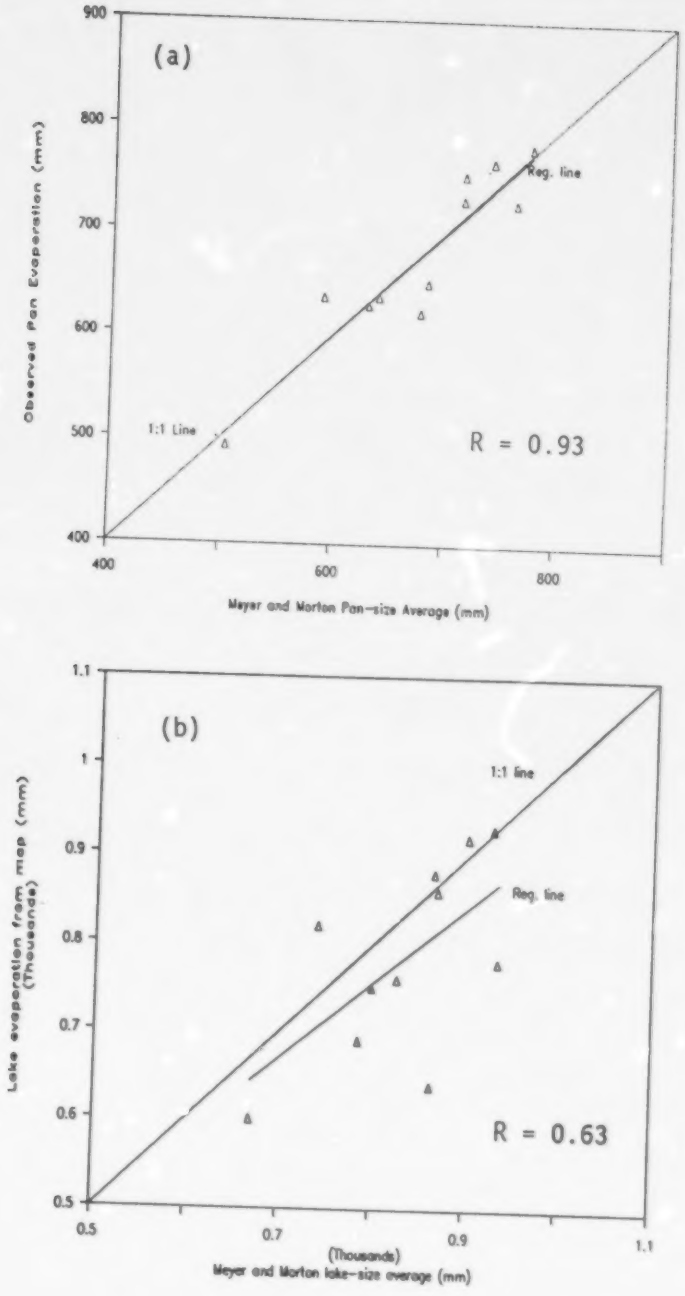


Figure 16: The relationship of (a) long-term three-month averages of evaporation pan observations and mean Meyer-Morton pan-size evaporation estimates, and (b) mean annual lake evaporation interpolations from the map and mean Meyer-Morton annual lake-size evaporation estimates for the 11 stations on the Canadian Prairies.

close to the one-to-one line (Figure 16b), an improvement over either of the individual map-Meyer and map-Morton regressions (see Figures 13).

As before, the poor correlation can be attributed to an inadequate control data base, namely the interpolated map values for lake evaporation. It is possible that, for certain applications such as water apportionment or reservoir design, the Meyer-Morton compromise may provide more consistent and more accurate estimates than either of the two alone, since it incorporates the wider range of variables afforded by both models. Of course, it also incorporates potential sources of error from both models as well. In any event, for the data used in this study, the Meyer-Morton compromise clearly simulated observed pan evaporation more consistently (correlation, 0.93) and more accurately (slope, 0.99) than either model alone.

4. SUMMARY

It is not possible, nor was it intended in this study, to evaluate the absolute accuracy of either the Meyer or Morton methods of estimating open-water evaporation. Instead, the objective of this study was to evaluate the degree of *consistency* between evaporation estimates from the Meyer and Morton techniques, using standard climatological data from eleven stations on the Prairies, including evaporation pan measures, as well as interpolated station values of lake evaporation from published maps.

Using the pan data as a standard, pan-size evaporation estimates were computed from Meyer's (1942) equation, substituting humidity and water temperature computations according to Martin (1988), and were also computed from Morton's (1983) formulation. For these simulations, it was found that, by adopting a value of 13.8 for the empirical coefficient, the Meyer formulation consistently over-estimated the average June-August pan-size evaporation by an average of +8.7%, while the Morton method, based on a different set of variables, consistently under-estimated this evaporation by an average -12.9%. A Meyer coefficient of 12.6 would have yielded the correct average pan-size evaporation with a mean error of -0.7% and a maximum error for any station within ±10%.

The linear correlation coefficients with the evaporation pan data were 0.85 and 0.83 for the annual three-month Meyer and Morton estimates

respectively, so that no significant advantage in either consistency or accuracy could be attributed to either method.

By computing a simple average of the Meyer and Morton estimates and comparing those computations with the pan-size data, the average deviation from pan-size values was reduced to -2.1% (from +8.7% and -12.9% respectively), while the relation with the pan-size values became almost one-to-one. Moreover, the correlation coefficient was improved to 0.93 for the long-term three-month averages.

It is difficult to recommend the use of Meyer based solely on this analysis because of the subjectivity involved in choosing the correct coefficient, and its limitation to three simple values (of 10, 11, or 15) according to Meyer. If the Meyer method is to be recommended at all, then a controlled field experiment is necessary in order to determine a more realistic range of values for this constant, dependent on water body size, exposure, roughness, and other environmental considerations.

Furthermore, by simply using actual water temperature data instead of estimates obtained from average monthly air temperatures, the Meyer method should provide somewhat more realistic estimates of evaporation. A 1 °C error in water temperature translates to almost a 10% error in computed evaporation using Meyer. In the absence of actual measures of water temperature, clearly a more definitive method of estimating water temperatures is required, perhaps through infrared estimates obtained from

high resolution satellite data or from routine aircraft traverses. Barring that, it may be better to estimate water temperatures based on actual air temperature over the preceding 2-3 months, as opposed to the climatological data approximations currently in operational use (Martin, 1988). The use of the latter approximations increases the uncertainty in Meyer estimates to more than 30%. With this being the case, other improvements, such as correcting for anemometer height, the method of computing vapor pressure, or barometric pressure adjustments, can be swamped by errors due to incorrect water temperatures.

Morton's methodology appears to under-estimate both pan-size and lake evaporation. The major reason appears to be the lack of a wind function in the formulation. In the Meyer formulation, for example, a wind speed of 16.5 km hr^{-1} effectively doubles the (no-wind) evaporation. This is borne out by the improved estimates and correlations with pan-size values obtained by averaging the Meyer values, which do incorporate a wind function, and the Morton values. Another source of error may result from the radiation term in Morton's formulation. Both of these potential-error sources should be investigated further, but this was beyond the scope of this brief analysis. Uncertainties in Morton estimates due to the lack of a wind function may increase with larger water body size, since the wind not only ventilates the evaporation, but also starts to create breaking waves, causing water particles to suspend in the air where they can evaporate more easily.

Of the two methods tested in this study, the Meyer formulation appears to have a slight, perhaps insignificant advantage over the Morton technique for estimating *pan-size* evaporation. This advantage appears to lie in the incorporation of a wind function in Meyer's formulation, and lack of one in Morton's. For lake evaporation estimates, we are unable to say whether either technique has any advantage over the other, primarily due to the lack of a control data set; i.e., a *measurement standard*.

To our knowledge, the Weyburn Reservoir experiments of 1960-61 (McKay, 1962) provide the closest approximation to such a standard for the Canadian Prairies. Attempts to carry out experiments using artificially-lined reservoirs have generally been unsuccessful. The Weyburn data represent the best Canadian water balance data set to date. Buckler and Quine's (1971) study implies an uncertainty in ground water estimates due to seepage of around ±15%. However, this seepage was based on winter-time estimates, when evaporation could be assumed to be negligible. McKay (1962) estimated that seepage might well be doubled during mid-summer. These facts suggest an uncertainty of ±30% in McKay's (1962) water balance estimates of evaporation from ground water fluxes alone. This, plus uncertainties due to other measurements suggests that the uncertainty in estimates of monthly evaporation from unlined reservoirs or lakes is of the order of ±50%. It was demonstrated that other methods, including evaporation pan data, the Meyer, and Morton techniques, also have an uncertainty of this magnitude.

In order to carry out a detailed evaluation of the Meyer, Morton, and other techniques for estimating evaporation, it would be necessary to obtain a data set valid for lake or reservoir size water bodies. In order to measure actual evaporative water loss from such a reservoir, a careful water balance would have to be carried out, where all other variables, especially the ground water and surface water fluxes, are known precisely. Since the accuracy of ground water estimates cannot easily be determined under natural conditions, the water fluxes must be controlled in any experiment designed to obtain data standards. This implies the need for a lined reservoir, so that the ground water flux can be reduced to near zero, allowing more precise evaporation *measurement standards*.

4.1 Conclusions

To summarize, this limited analysis leads to the following conclusions:

1. **Evaluation Problems:** The half dozen or so most popular methods for estimating open-water evaporation are generally based on different theories. These include the energy balance approach, mass transfer, water balance, and turbulence methods, and the various semi-empirical approaches. This makes it difficult to carry out intercomparison studies, so that results are often inconclusive.

2. **Consistency of Results:** Given the same environmental and atmospheric conditions, Meyer's formula yielded slightly higher correlations with evaporation pan observations than did Morton's technique. The differences, however, are not significant enough to infer which of the two techniques provides the most consistent results.

3. **Accuracy of Meyer versus Morton:** Meyer's seasonal values of lake evaporation over-estimated the pan-inferred values by 8.7%, while Morton's values under-estimated by 12.9%, giving a slight edge again to Meyer. Again, the differences are not significant enough to infer which is the better technique for these cases, especially when one considers the subjectivity involved in choosing the Meyer coefficient (13.8 in this case), the pan coefficient (0.72), and other subjective features of these semi-empiric techniques.

4. **The Meyer-Morton Compromise:** A simple average of the monthly values of Meyer and Morton estimates provided more consistent estimates of both pan-size and lake evaporation. This also gave the most accurate pan-size estimates for the full range of values (linear regression slope, 0.99).

5. **How to Evaluate:** Questions regarding the accuracy of one technique over another for estimating lake evaporation cannot be resolved using climatological data sets where only empiric relations with

evaporation are known. Because evaporation cannot be measured directly, the only way to evaluate such techniques for area evaporation is by way of a *controlled* water budget experiment. Technological improvements in instrumentation and other required field equipment provide much better capabilities for success than similar experiments of 30-40 years ago.

6. **Limitations of the Evaporation Pan:** After several decades and many field studies, it is still not clear to what extent, and under what circumstances, the pan is representative of evaporation from natural water bodies, especially large reservoirs. Indeed, the literature quotes pan coefficients from 0.3 to 1.4, although for lake evaporation, a value around 0.7 is most often used. We emphasize, however, that evaporation pans, in a controlled field setting, are indeed representative of evaporation from reservoirs of the same size and type as the pan. In this sense, our evaluation of Meyer versus Morton accuracy for pan-size evaporation should be valid.

7. **Advantages/Disadvantages of the Meyer Technique:** The Meyer method, though empiric, has a sound physical base. Its major advantage may be the incorporation of a wind function to account for advection. Its greatest drawback appears to be the subjectivity involved in the choice of the Meyer constant. At the same time, the statistics and rules behind this constant were developed for a range of settings

in the U.S., and its applicability to other locations has never been evaluated to our knowledge.

8. **Advantages/Disadvantages of the Morton Method:** The Morton technique, is based on the energy balance concept, so that in theory, it is applicable anywhere in the world. The main disadvantage would seem to be the lack of any wind function, and because of this, the technique appears to under-estimate evaporation. This may be a serious drawback in the dry, windy conditions of most Prairie locations.

4.2 Recommendations:

Our analysis and conclusions suggest a number of recommendations:

1. **Evaluating the Consistency of Different Techniques:** More detailed analyses stratified by region and season, and use of other existing data sets, including the re-examination of field research data such as the Weyburn Reservoir studies may provide more useful answers to the consistency question.

2. **Evaluating the Accuracy of Different Techniques:** Clearly, questions regarding the accuracy of one technique over another can only be resolved through a controlled field experiment, where accurate measurement standards can be obtained. Extensive tests using lined

reservoirs (to reduce inaccuracies inherent in ground water and surface water measurements), and applying the water balance approach to a wide range of reservoir sizes, field exposures, and meteorological conditions, are ultimately required to evaluate existing methods and technologies, and to propose new methods or models for estimating evaporation.

3. **The Evaporation Pan:** In the absence of an operational replacement instrument for the pan, it would seem logical to retain its use for some time to come. Any field experiment designed to evaluate various methods should include varying sizes of pans in different exposures, sunken, raised, and floating.

4. **The Meyer Technique:** Uncertainties in the Meyer technique would be reduced by: (a) using actual water temperatures (rather than statistical relations with mean air temperatures); new satellite data retrieval methods seem a logical way to go here; (b) developing a more critical set of rules for determining the value of Meyer constant to use in a given location, exposure, and sets of hydrometeorological conditions.

5. **The Morton Method:** The inclusion of a wind function might reduce the uncertainties in values obtained from the Morton method, and improve its consistency with evaporation estimates from other techniques.

6. **New Empirical Techniques:** The fact that a simple Meyer-Morton average value was both more consistent and more accurate than either technique alone, simply confirms that each has certain advantages. Even a statistical combination of the variables combined in both methods (or derivations of same) may lead to an improved operational estimation technique.

7. **Use of Latest Technology:** Any controlled field experiments (see no. 2) should emphasize state-of-the-art instrumentation and attempt to develop reliable means to transpose point measurements into accurate estimates of total evaporation from water bodies. These should include recent Bowen Ratio and Eddy Correlation techniques.

In spite of the fact that evaporation is the single most important hydrometeorological variable on the Prairies, more especially during the growing season, there is still no measurement standard by which to evaluate the proliferation of estimation techniques, each driven by one of several sets of physical laws in varying degrees. We are unable to provide evaporation estimates with any great confidence, say, accuracy to within ±10%, or even to recommend precisely what inputs to provide to a new operational technique or model. Undoubtedly, part of the problem is that, while evaporation processes are basically well understood, we cannot measure the quantity directly, and therefore cannot estimate it with real confidence. We can only surmise, therefore, that the problem is more of

a technological one, and in the past, perhaps has been of less scientific interest. If nothing else, we hope that this study has highlighted some challenging scientific, as well as technical problems.

Increasing concerns over climate warming due to greenhouse gases, and the possible scenario of more frequent and more intense droughts on the Canadian Prairies, suggest a critical need to evaluate current operational techniques, and to develop improved techniques for measuring or estimating evaporation. Past neglect of this area by the research community is evidenced by the fact that, in Canada, we are currently poorly equipped to mount even a modest field research effort. It is now the responsibility of the hydrometeorological research community to meet this challenge before the need becomes a socio-political one.

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